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Analysis of temperature variation in the lakes of the central-eastern Pyrenees

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Al mondo che avrei voluto cambiare

e che inesorabilmente verge verso un ostile fato.

Alle persone che lo popolano

e che tentano disperatamente di cambiarlo con le proprie azioni.

Alla nostra amata Terra

martoriata dallo sfruttamento e dall'avidità in nome del profitto.

ABSTRACT

Mountain lakes are important indicators of climate change.

In this thesis work, surface water temperatures were studied for a set of lakes located in Catalunya, Spain's central-eastern Pyrenees chain (11 lakes). The temperatures examined are collected periodically by downloading data collected by continuously measuring thermistors located, individually or in chains (depending on the depth of the lake where are installed), within them. They measure 1 temperature value per hour and at the same time the light intensity that reaches the thermometer that gives us, in some cases, a minimum information on the hourly solar irradiation allowing us to evaluate the goodness of the first datum.

In this report, the period 2015-2022 is considered as the reference period, unless otherwise indicated. This period served as a starting point for the calculation of the various parameters and indicators including Degree Days (DD) and its cumulative function ADD. These data represent the initial data for the interpretation of the evolution of the climate within the Pyrenees Mountain range under the effect of Climate Change. Hourly values of air and surface temperature of water basins have been made available, from which daily, monthly, and annual average values of the main statistical variables have been summarized. The series were in some cases incomplete and, where possible, the data sets were reconstructed through the calibration of a linear regression model of the thermistor chains present inside the lakes (installed from 2019). In other cases, it was decided not to reconstruct the data to avoid making errors in the approximations: for this reason, the complete values of the series are not always present in the representation of the result.

The summer of 2022 presented itself as the recorded hottest season ever and recorded the highest annual temperature values in the period considered, but also accompanied by an extreme drought phenomenon, which may increase the local evaporation in the basins, thus reducing water inflow into the lakes. ADD values present a considerable detachment from summer air temperatures, which can also be explained by an early melting of the ice cover present in the winter season in this type of glacial lakes that have always formed. Lakes without surface water inflows have a lesser effect of drought, as their only water inputs are from precipitation, in form of rain and snow and underground springs. For this reason, they represent a good field of study as they make it easier to compare before and after and can be assumed as isolated systems where the only external influences are given by precipitation and climatic characteristics. In addition, the presence of several lakes on the same territory allows an aerial comparison of the phenomenon as well as a verification of the events that occurred in a single lake.

Overall, a statistical analysis of the data was carried out demonstrating a strong linear correlation between the maximum temperature reached in the summer season (the period between ice-off and ice-on) and the ADD. The warming of the waters also affects the formation, as well as the quality of the ice that allows to preserve the life of the whole lake in the winter season (of which, however, there is no information). Equally interesting parameters, but not analyzed in this context, are the reduction of the surface level of the lake, as well as the level of eutrophication of the same, *i.e.* the mechanism by which the lake naturally attenuates the presence of nutrients (algal bloom), and biodiversity.

From the thermal point of view, the lakes are gradually exerting conditions of instability even in periods of chemical equilibrium or oxygenation (interseason mixing): in this context the effects on biodiversity become evident. In addition, the reduction of ice cover is a function of temperature, but also of precipitation: less snow falling in winter and early melting are symptoms of an increase in the temperature of the lake to which the reactions described above follow. No

significant changes were observed in the period (days) related to the presence of surface ice or free water.

An interesting result emerges from the analysis of inter-lake and intra-lake variability of ADD. The inter-annual variability is much more significant than the variability expressed between lakes. Therefore, observations and results obtained for a single lake would be extendable to all basins in the region; This is also true for climatic conditions which, except for some minimal local variability, are homogeneous throughout the region. Interesting, is the relationship obtained between the altitude and the value of ADD: it decreases with increasing altitude also as a function of the relationship with the air temperature that follows the same trend. A significant correlation was also obtained for the maximum annual temperature reached and the number of days in which the lake's water temperatures were above 20 ° C.

A lake is a source of life: for this reason, analyzing the seasonal variability of the same allows you to monitor the state of fauna and flora within it under the effect of climate change. Not all species are able to adapt to changes by developing resilience characteristics. In some cases, the temperature increase recorded does not allow the development of the entire life cycle of some species of amphibians (such as the *Rana temporaria* or the *Alytes obestetricans*). The increase in temperature and consequently the ADD affects, therefore, the food chains, which allows the effects of the change to be observed immediately.

Summary

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INTRODUCTION

In the last 150 years, the global surface temperature of our planet has increased by 0.85 °C (more precisely +1.01°C since 1880, Figure 1). This change was largely determined by the increase in carbon dioxide and other anthropogenic emissions released into the atmosphere. Most of the warming has occurred over the past 35 years (as seen in the graph in Figure 1). The graph shows the global surface temperature variation: nineteen of the warmest years have been recorded since 2000, except for 1998 (a clear outlier of the series). The year 2020 tied with 2016 the warmest year ever recorded since recording began in 1880.

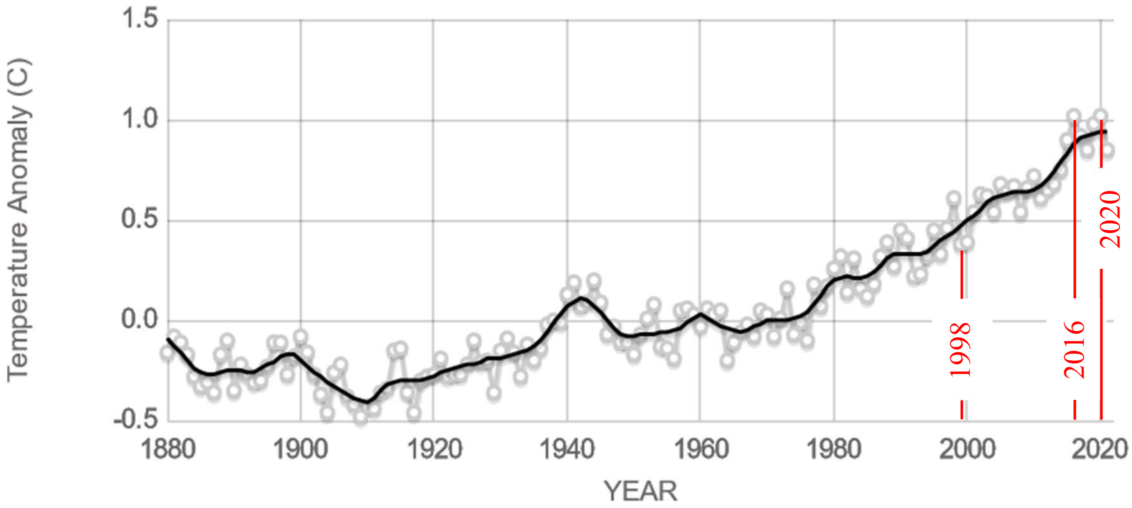


Figure 1. Global land-ocean temperature index. Source: NASA's GISS.

2020 is considered one of the hottest years in history, or rather, since there are records of temperature measurement (1880), presenting global surface temperatures of 0.6 ° C above the average of the thirty-year period (1980-2010) combined with a geographical spread of unprecedented heat waves. This temperature rise was also perceived by the biosphere, which due to high temperatures suffered an earlier start of the season, and a later end of the season resulting in a longer growing season. The year 2022 showed similar characteristics and presented a year of severe drought throughout the Mediterranean area and beyond.

Among the ecosystems that have been most affected by this temperature variation are mountain environments, specifically those analyzed in the Pyrenees and Alps. Mountain ranges are suffering from the effects of climate change and must deal with rarefaction of rainfall, especially snowfall, and melting glaciers.

In the Pyrenees, the temperature rose by 1.2 °C in the second half of the twentieth century, compared to pre-industrial times, thus recording an increase of 30% more than in the rest of the world (where the increase was 0.85 °C). The report of the *Pyrenean Observatory on Climate Change* (OPCC) of Zaragoza, precisely highlights this average increase in temperature generalized on the mountain range with few differences between the northern and southern areas, specified the coordinator of the organism Idoia Arauzo Gonzalez "*it is as if these mountains were afflicted by a fever, a symptom of serious illness* ". Also, according to the body, this change, due to climate change, could lead to undergoing, by the mountain range, irreversible consequences and profound changes for ecosystems and subsystems, sometimes accelerating the degradation process of some areas, now causing a loss of biodiversity.

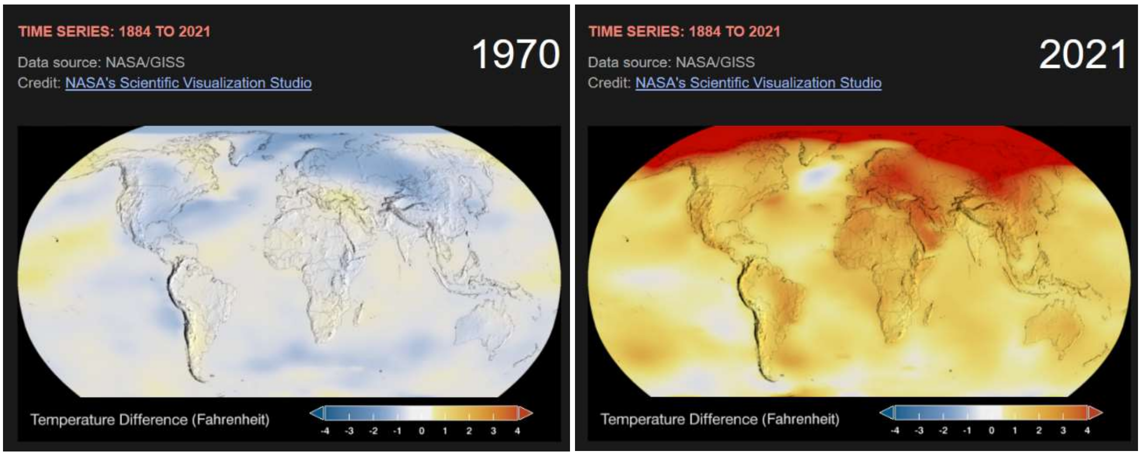


Figure 2. Framework of global surface temperature change. In dark blue are represented the coldest than average areas, while in dark red the warmer than average areas. The source map attenuates short-term temperature changes (noise) through a moving average of 5 years. Source: NASA's GISS.

Half of the glaciers on these ranges have disappeared in the last 35 years, giving way to constellations of small lakes of glacial origin. According to the study, a 50% decrease in the snowpack is expected over the next 30 years in the Central Pyrenees, as well as an increase in increasingly frequent extreme phenomena (such as the recorded drought of the BC alternating with torrential rains). Early thaw and delayed and short-term freeze periods with consequent effects on flora and fauna. The latter could undergo changes in the growing season, while exotic species could enter the territory, colonizing and in the worst cases replacing native species and causing their extinction.

The Alps, on the other hand, experienced an exceptional increase in temperature between 1901 and 2000 equal to 2 ° C: double the average of global warming. Here the changes in precipitation have been recorded as more moderate, but also in this case there is a lower permanence of the snowpack at low altitudes and the substantial retreat of the glaciers, as well as the consequent triggering of landslides and avalanches (such as last July 4, 2022, the detachment of a huge portion of the Marmolada glacier, province of Trento, Italy). As mentioned in the case of the Pyrenees, all phenomena destined to intensify in magnitude and frequency with increasing climate change (IPPC, 2007). Precisely because of their morphological characteristics, alpine lakes are among the aquatic ecosystems most threatened by this change.

In general, global warming, and therefore climate warming, is causing important effects on the atmosphere, hydrosphere, cryosphere, and biosphere as well as on the complex network of interactions and biogeochemical cycles between them. In this master thesis, we will analyze the temporal evolution of water temperatures in high mountain lakes, and how they are related to meteorological forcing and the characteristics of the lakes. In fact, according to many studies, there are close connections between climate, thermal properties of lake bodies and physiology of aquatic organisms, abundance of the population, and structure of trophic communities (Carter J. et al 2012).

This document deals with research carried out within the framework of the European cross-border research project LIFE RESQUE ALPYR (www.liferesquealpyr.eu) and aims at the collection and analysis of data on the temperatures of glacial lakes in this context. This analysis is carried out with the collaboration of the Centro de Estudios Avanzados de Blanes (CEAB) part of a research center of the Consejo Superior de Investigaciones Científicas (CSIC), Spain.

Chapter 1

Theoretical notes of phenology of mountain lakes

1.1 The hydrosphere

The hydrosphere constitutes the set of water parts of the Earth and is undoubtedly the second most important subsystem, after the atmosphere. It includes oceans, inland seas, rivers, lakes glaciers, water in the atmosphere, and groundwater: the main component, however, is the oceans, composed of salt water, where 97% of the total water available on our planet is concentrated. For this reason, the hydrosphere assumes an important climate significance.

Table 1. Distribution of water availability on Earth. Source: Cuadrat &Pita, 2011.

Deposits		Volume (km^3 x 10^3)	% of the total	Range of value in recent bibliography (km^3 x 10^3)
Oceans		1.350.000,0	97,403	1,32 - 1,37 x 10^6
Atmosphere		13,0	0,00094	10,5 - 14,0
Continental		35.977,8	2,596	
	Rivers	1,7	0,00012	1,0 - 2,1
	Lakes	100,0	0,0072	30,0 - 150,0
	Inland seas	105,0	0,0076	85,4 - 125,0
	Groundwater hood	70,0	0,0051	1,5 - 150,0
	Groundwater	8,200,0	0,592	7,0 - 330,0 x 10^3
	Ice and glaciers	27.500,0	1,984	16,5 - 29,2 x 10^3
	Biota	1,1	0,00008	1,0 - 50,0

Water on Earth, thanks to its large volume, guarantees an abundant reserve for the development of the different phases of the hydrological cycle increasingly altered by the effects of climate change that are expressed above all in more evident climatological variations at the local level. In this sense, the hydrosphere exerts a clear thermoregulatory influence on the climate: this is because the waters have a conservative action, due to their high specific heat capacity, testified by the reduced daily and annual thermal amplitudes.

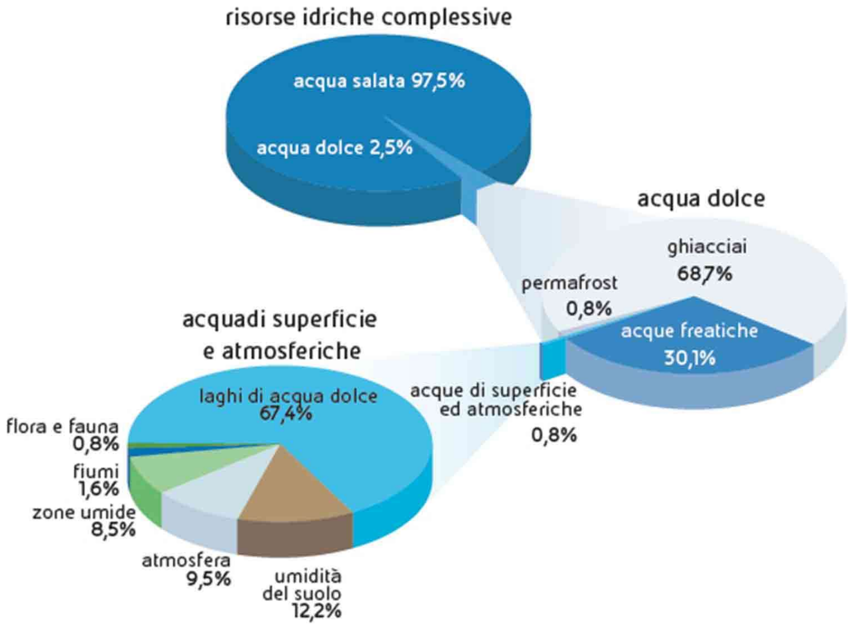


Figure 3. Percentage breakdown of the distribution of water resources on land. Source: Personal Notes.

As mentioned, the thermoregulatory influence, exerted by the atmosphere on the climate, is more exerted at the local level, or in the presence of substantial water masses (large lakes or inland seas), or more generally through the action of the oceans. This happens thanks to the fact that water is a thermally very conservative fluid. First, the energy is transported to the bottom, distributed in a large volume of water by vertical and horizontal mixing through which it is possible to store large amounts of heat, which the mass of water then exchanges with the atmosphere through more or less long coupling processes, which is why large masses of water provide considerable inertia to climate change. Secondly, the high heat capacity of water (see Table 2) plays a fundamental role in the cooling and heating times of the same material, when compared with others. Thus, it takes a lot of energy to raise the temperature of a mass of water and vice versa, that is, it must disperse a large mass of water to cool down. Water, on Earth, therefore, performs the dual function of terrestrial thermostat and reserve of thermal energy to which can be added the function of transporting heat, through sea currents, for the globe: it is estimated that one-third of the average terrestrial thermal exchange is carried out by the oceans (Cuadrat & Pita, 2011).

Water receives and absorbs most of the solar energy, in the form of light radiation, which reaches the earth's surface; it transmits it in depth and then re-emits it into the atmosphere in the form of long-wave radiation and heat – energy – by means of evaporation The transmission of heat to water takes place by diffusion and above all, within it, through turbulent currents that transport water vertically mixing salinity and temperatures. However, the behavior loses uniformity with increasing depth. Then, a decreasing gradient is established as a function of increasing depth that allows to identify of a layered structure.

Table 2. Thermal properties of different natural substances. Source: Cuadrat &Pita, 2011.

Substance	**Condition**	**Density 10^3 kg/m^3**	**Specific heat 10^3 J/kg/K**	**Calorific capacity 10^3 J/m^3/K**	**Thermal conductivity W/m/K**
Air	20°C, Pamb., staz.	0,0012	1,00	0,0012	0,026
Water	20°C, Pamb., staz.	1,00	4,19	4,19	0,58
Ice	0°C, puro	0,92	2,10	1,93	2,24
Snow	Fresh	0,10	2,09	0,21	0,08
Sandstone soil(n=40%)	Dry	1,60	0,80	1,28	0,30
	Saturated	2,00	1,48	2,98	2,20
Clay soil(n=40%)	Dry	1,60	0,89	1,42	0,25
	Saturated	2,00	1,55	3,10	1,58

1.2 The biosphere

The biosphere is the set of living beings present on planet earth and their relationships: organisms influence the environment and vice versa.

The set of plants and animals, including man as part of the system, is a very recent classification (Cuadrat & Pita, 2011) which also includes the impact of the latter on the climate, because although the forms of reaction differ widely, the biotic elements are sensitive to climate and in turn can influence it. Specifically, biomass plays a fundamental role in the carbon dioxide balance, while animals interact with the earth's surface and its changes are reflected in climatic variations through food and habitat. In this context, as is known, life is organized on hierarchical levels of complexity with gradually increasing systems, potentially increasingly complex and varied. These systems are self-organized, and the biosphere shows a capacity for homeostasis, *i.e.* regulation of its composition and structure (although not comparable with that of an organism) and homeores is, *i.e.* the regulation of its whole processes and exchange through negative feedbacks. These two concepts are fulfilled when, due to climate change, an ecosystem reorganizes itself by practicing a selective adaptation to the new habitat.

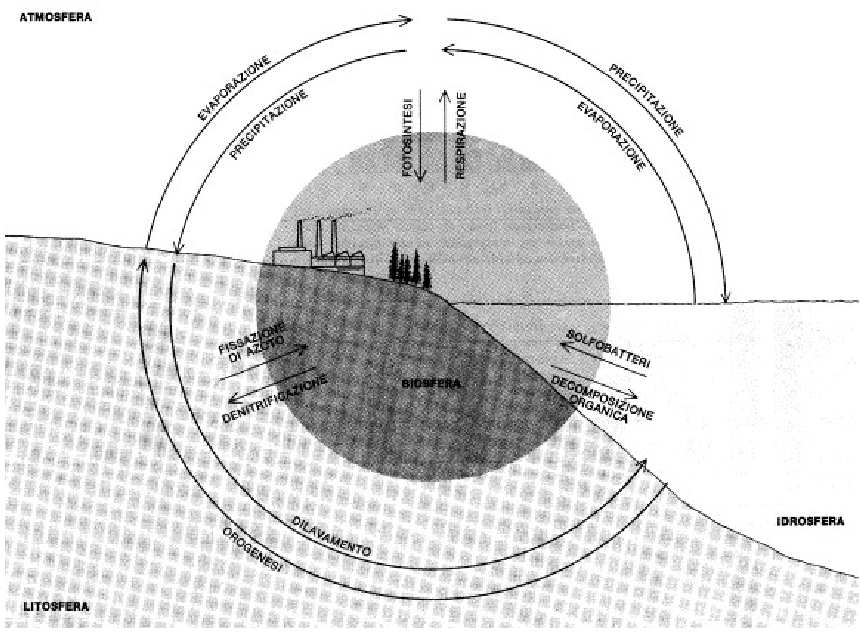


Figure 4. Representation of the integrated terrestrial system: interaction between biosphere, hydrosphere, atmosphere, and lithosphere through the main biogeochemical processes present. Source: Notes on Applied Geomorphology, University of Genoa, 2019.

1.3 The lake system

Lakes are one of the components of the hydrosphere and, as seen in Table 1, less than 0.01% of the total water available on Earth. So, globally, they have very little influence on the hydrological water cycle, but locally they represent important ecosystems. They allow a close interaction between the biosphere and the hydrosphere and locally can also influence its climate.

By lake we mean a mass of fresh water, large, collected in continental terrestrial depressions. These masses of water can have different origins and reach a condition of water balance through the feeding of springs, glaciers, or precipitation – solid or liquid – which affect chemical-physical parameters such as temperature, salinity, and acidity of the water, and the outflow only through evaporation into the atmosphere and, if present, emissary rivers or groundwater.

The water moves by gravity and flows along the lines of maximum slope and its speed in lakes decreases a lot, compared for example to the average speed in a mountain stream equal to 3 m/s, it turns out to be around 1 cm/s. This low speed means that, within the lake system, the movement of water depends on climatic conditions and is no longer the result of the gravitational effect. Solar radiation provides thermal energy, which, combined with the mechanical energy supplied by the wind, contributes to determining the displacements of the mass of water within the depressions and therefore its oxygenation thanks to contact with the atmosphere.

1.3.1 The hydrology of lakes

Each lake is inserted within the hydrographic network of the geographical area where it is inserted, regardless of its origin: therefore, each lake has its own hydrological balance understood as the quantization of water inputs and losses.

The contributions consist of:

1. inflow through tributaries A;
2. inflow from surface runoff and non-channeled runoff R;
3. direct rainfall on the surface of Lake P;
4. inflows to the lake by underground routes As.

Losses, on the other hand, are attributable to:

1. evaporation E;
2. underground outflow Ds;
3. outflow through emissaries D.

The hydrological balance equation then becomes:

$$A + R + P + A_s + \Delta h = D + E + D_s \tag{1.1}$$

Where Δh indicates the variations in the amount of water within the lake basin.

Another fundamental parameter for the evaluation of the state of a lake is its *Average Time of Residence* (TMR) which allows to establish the time necessary for the replacement of the entire volume inside the basin. It is calculated as a ratio between the volume of the lake and the flow of its emissary, but it tends to be an underestimation as it would be necessary to consider numerous other factors not always immediately determinable.

1.3.2 Currents

The water of the lakes is not stationary, but whirlpools or waves can form on its surface due to various causes, among which the main one is certainly the action of the wind on it. The phenomenon is called *Wind Drift* and corresponds precisely to the movement of the waters caused by the atmospheric wind that laps the surface and exerts a force: as a consequence, the water is transported in the direction of the wind, but not being able to accumulate, vortices (or *eddy*) are generated in depth that mix the waters and impose on it a return current towards that of the wind.

From literature, the effect of *the Wind Drift* has a magnitude equal to 2-3% of the average wind speed, or the return current. In this way, the water flowing upwind is transported back into the lake, in depth, as a return current. This significantly affects the temperature of the waters of the lake which, with this action of mixing the waters, can be modified in a positive or negative way (depending on seasonality) even outside the periods of phenological mixing of the mountain lake; also the action of the wind guarantees, together with the mixing, the recharge of oxygen to the entire water column and with it also all the other solutes, including nutrients, which in this way can be distributed evenly within the lakes. A complete recirculation of the water column is essential for oxygenation and, consequently, for the development of life within the lake.

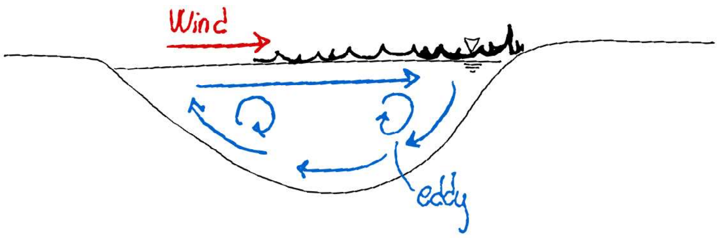


Figure 5. Schematization of the phenomenon of Wind Drift on the surface of a lake.

1.3.3 Temperature and density

The water temperature of a lake is a fundamental physical parameter to assess the quality of water and the consequent state of health of a body of water. In fact, temperature influences water chemistry, and consequently the functions of aquatic organisms. This parameter can affect the amount of oxygen dissolved in water, the rate of photosynthesis of algae and aquatic flora, the metabolic rate of organisms as well as sensitivity to toxic waste, parasites, and diseases. As far as the biotic component is concerned, the temperature can also significantly influence the breeding, migration, and summer season of aquatic organisms.

The temperature of the surface waters of a lake is closely linked to the air temperature: therefore, it undergoes an interannual variation on a regional scale. Clearly, in mountain lakes, the formation of the ice cover on the surface of the lake in the winter months inhibits this correlation (Figure 6).

In the summer months, the trend of the two temperatures is perfectly comparable. In general, the overall statistical correlation between the two temperatures is 0.75. The interannual variability of air temperatures, represented by seasonal temperatures in Figure 7, shows a positive influence on the average surface water temperature: in spring, the strongest effects of air temperature on lake thermal variables are recorded (Sabas et al. 2021).

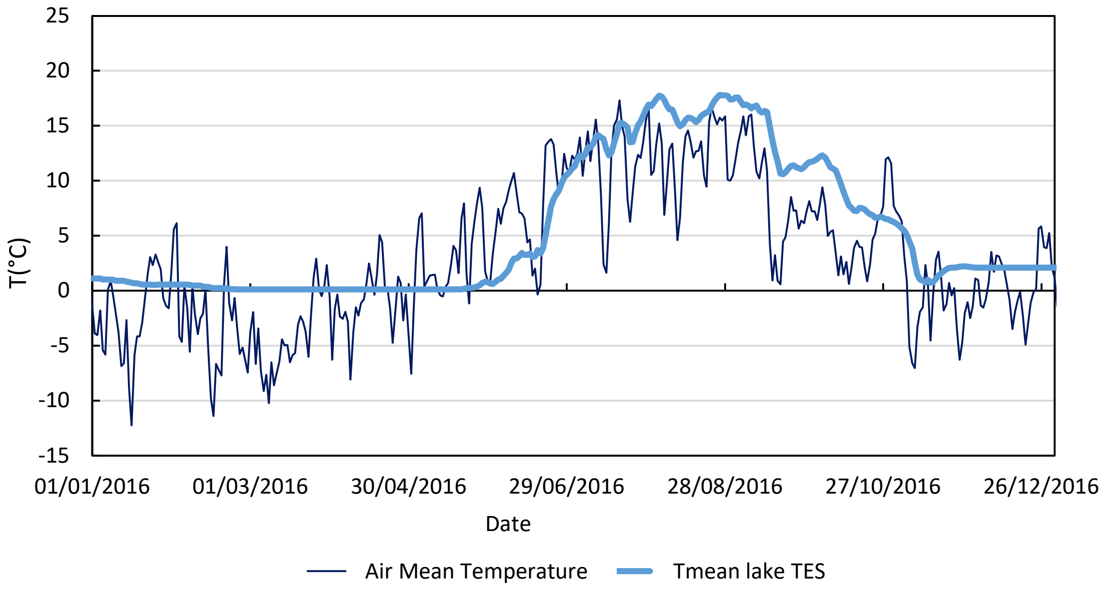


Figura 6. Graphic showing the annual trend of air temperature (Redon weather station) and surface water of Lake Tres Estanys Superior (Pyrenees, Spain) for the year 2016.

The temperature of the waters of a lake at a given time of the year depends strictly on its thermal balance, *i.e.*, the difference between heat inputs and losses. It should be noted that the temperature of the waters of high mountain lakes depends primarily on the altitude of the lake (Sabas, Mirò et al. 2021). As air temperature decreases with altitude and also water temperature decreases in altitude due to the heat transfer between air and water: thus, showing an inverse relationship with all the thermal variables, turns out to be the most significant variable that affects the variations and climatic conditions. Secondly, the orography of the site, the topography, and the solar radiation are equally significant. The geomorphology of the lake and the catchment plays a major role in the average water temperature, while the geographical coordinates have had a limited effect.

As for the internal temperature of a lake, it can vary from the bottom to the surface during the year, expressing itself under very different thermal profiles depending on the season. This happens especially in lakes in temperate climates – such as those in our latitudes. In these climates' lakes stratify in summer and winter due to the variation in water density between the surface and the bottom of the lake. Density-based stratification is clearly a function of water temperature, especially surface water temperature heated by solar radiation in summer, and isolated by snow and ice cover in winter. This is because water has a maximum density at 4 °C (see Figure 9): this means that water at a higher or lower temperature – the solid state of water floats on the liquid one – to this is less dense, that is, lighter and therefore can float on a layer at such a temperature that is in any case heavier. In conclusion, the density of water depends on the temperature in a non-monotonic way. In addition, buoyancy dampens the turbulence produced by Share (shear stresses) for which the Reynolds number is greater than 1, while the Monin-Obukhov length (L_M) has a small and positive value: overall they confer stability conditions.

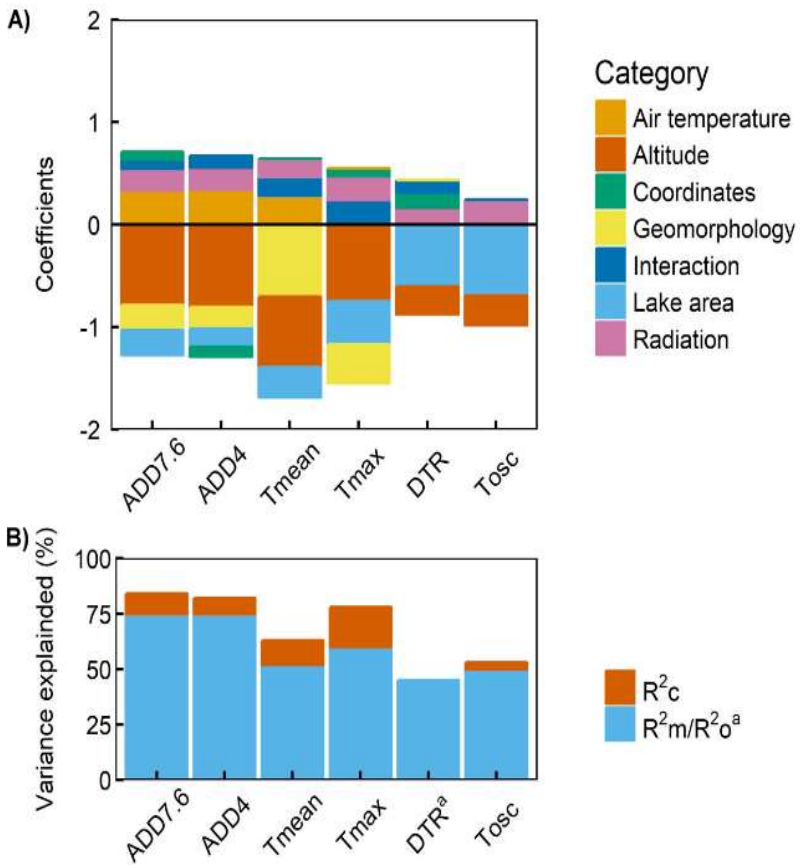


Figure 7. Using mixed regression models, the relationship between the variables considered is shown. Source: Sabas et al., 2021.

Solar radiation is the main source of heat in these systems: it gives heat to water that has a low tendency to release heat by molecular diffusion (vertical dispersion coefficient 10^{-5} cm^2/s). This condition is such that the epilimnion, the surface layer, is more influenced by the external temperature. The layer immediately below is called metalimnion, the temperature undergoes an important variation in temperature with depth. Depending on the depth of the lake there may also be a layer – called hypolimnion – whose temperature is maintained at a temperature of 4 °C almost at a cost throughout the year.

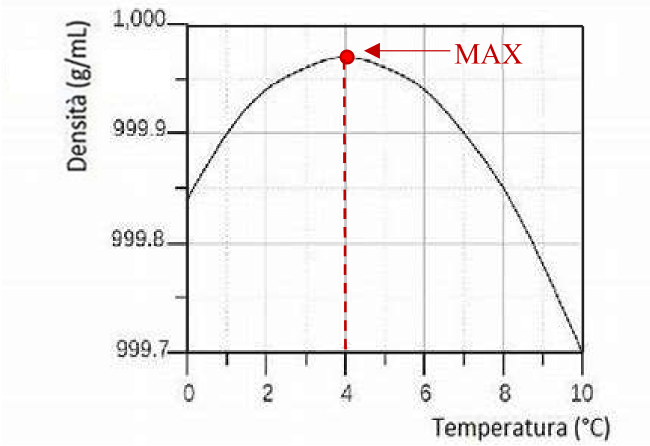


Figure 8. Graphic showing the trend of water density as a function of temperature. Source: personal notes.

In this sense, the turbulent mixing of water that occurs by the wind (Section 1.3.2) allows the gases dissolved in water (O_2 and CO_2) to be also exchanged with the atmosphere through the free surface of the water. Therefore, since the surface layer of the lake waters receives the most solar radiation, therefore heat, it is also the layer in which the photosynthetic organisms are located. When these die, they settle up to the hypolimnion ensuring the recharge of nutrients of this layer.

1.3.4 The thermal properties of a lake

The thermal properties of a lake are the most important physical factor in determining the annual and daily cycle of a lake: in fact, these directly influence the chemical characteristics of the waters and consequently the ecology of the organisms constituting its ecosystem. The water column inside a lake can have the same temperature from the surface to the bottom, or have a geothermal gradient, most of the time, high. The higher the vertical thermal gradient, the lower the exchanges.

1.3.4.1 Reverse Stratification – Winter

During the winter season, if the surface temperature drops below 4 °C, with the potential formation of an ice cover, due to the anomaly of water density, the so-called reverse stratification will occur. Epilimnion, *i.e.* the surface layer of the stratified water of a lake, is the layer subject to the greatest interference deriving from the atmosphere with which it is in contact and with its agents (solar radiation, wind, evaporation, etc.). Normally, it is located above the layer of greater thermal discontinuity called the hypolimnion. Under these conditions, the colder, but still lighter, epilimnion, floats on the warmer and therefore heavier hypolimnion due to the anomaly of the water density curve (presented in Section 1.3.3). This thermal stratification means that the coldest layer is the surface layer, while the warmest layer (around 4 °C) is the deepest. The process then involves a subsequent cooling of the surface water until the formation of ice which, having a density at 0 °C equal to 9/10 of that of the water below at 4 °C, floats on the underlying liquid surface. The formation of ice inhibits the phenomenon of wind *drift* – therefore the mixing condition of the lake is zero – which further prevents the mixing and displacement of the mass of water given by the same action of the wind, thus making the reverse stratification stable.

On a biological level, low temperatures slow down the metabolism of all living creatures (fauna and flora) which leads to a reduction in the oxygen present in the waters of the lake. Because of its difference in density, ice allows fish and other life forms to stay alive and complete their life cycle. In addition, it can become very dense due to possible snowfall, preventing a significant light supply given by the penetration of solar radiation into the deeper layers of the lake. This condition means that the photosynthetic processes, by algae, are further slowed down, until they cease in dark conditions and that the direct diffusive exchange of oxygen, between the waters and the atmosphere, is completely inhibited. Therefore, in depth we will have the least oxygen condition, as most of it will be concentrated in the middle layers of the lake. In conditions of abundant snow cover, very prolonged in time and very low temperatures, oxygen could be completely depleted causing the killing of fish species during the winter season.

1.3.4.2 Turnover - Spring

The waters of a hypothetical lake in the temperate region, at the end of the winter season, will present at all depths an equal temperature of about 4 °C. This is because the ice in the season melts when the lake, heated by more intense solar radiation – higher temperatures – is almost in isothermal conditions and this leads to a loss of water stratification. As temperatures continue to rise, the ratio between the temperature of the surface, in contact with the air, and that of the bottom tends to 1 allowing mixing between the layers. The action of the wind, which is no longer inhibited by the ice sheet, allows the mixing of the most superficial waters in contact with the atmosphere. The water circulation recharges with oxygen, dissolved first in the most superficial layer, then in the entire water column. The lake in this season will assume a homogenous temperature along its entire depth ensuring a uniform mixing of contaminants and nutrients: the frequent spring precipitation brings not only a recharge of water, but also an influx of nutrients deriving from the corrivation of rains along the landscape. The nutrients cause algae bloom and zooplankton bloom creating an upward flow of nutrients through the food chain and trophic relationships within the lake. The system is in an unstable condition.

1.3.4.3 Thermal Stratification - Summer

In summer, solar radiation leads to an increase in the temperature of surface waters, consequently decreasing its density compared to deeper waters. In this context, the wind is not strong enough to cause a mixing of the lake through mechanical work done on surface waters. The immiscibility between warmer and less dense surface waters and cooler and therefore heavier underlying waters contributes to the distribution of heat from the surface layers to the deeper ones according to a positive thermal gradient. The surface layer – epilimnion – thickens with the progress of the season and will become warmer resulting clearly separated from the cold deep waters – hypolimnion – by a transitional layer called metalimnion which is distinguished by a sudden decrease in temperature as the depth increases. In this system, the concentration of dissolved oxygen within the waters of the lake decreases according to depth gradient: in fact, there is an effective exchange of heat and chemicals in the epilimnion, but practically zero in the deep waters. In addition, layering results in nutrient isolation at the bottom of the lake. Bacteria consume nutrients and dead organisms causing oxygen dissolved in water to be depleted faster than it is replaced. If the lake is very productive, the oxygenation of organic matter can completely consume the oxygen dissolved in hypolimnetic waters, which cannot be recharged, generates anoxia conditions (absence of oxygen) clearly incompatible with most of the life of aquatic organisms. Anaerobic bacteria, on the contrary, consume organic material more slowly than aerobic ones, generating, as a product of metabolism, hydrogen gas that remains confined to the lower layer of the system, contaminating it until seasonal cooling allows the subsequent mixing of water. It is clear that the hot water of the summer season contains less oxygen: this is also due to chemical conditions of solubility of oxygen in the water. In fact, solubility decreases with increasing temperature in an inverse proportionality relationship: this translates into a smaller amount of gas needed to reach 100% saturation by surface water compared to groundwater. Therefore, large algal blooms, which exceed oxygen supply when they decompose after death, can cause summer killings of fish species.

The stratification generally persists until autumn.

1.3.4.4 Turnover – Autumn

The lake, in autumn, mixes completely once again when the solar radiation decreases and causes the cooling of the epilimnion to the approximate temperature of the hypolimnion: this causes a descent of the denser water also causing a thinning of the layer in which the temperature steep decrease usually takes place, or the metalimnion. When the lake is almost isothermal (around 4°C), there may be enough wind energy to mix the lake well allowing the lake to be completely replaced. Now the lake is in unstable conditions with mixing between layers and uniform dissolved oxygen distribution due to exposure of a larger volume of water to the atmosphere, as well as nutrient mixing. Autumn turnover is often very short and rapid. Subsequently, the decrease in temperatures and the formation of surface ice gradually reduce mixing.

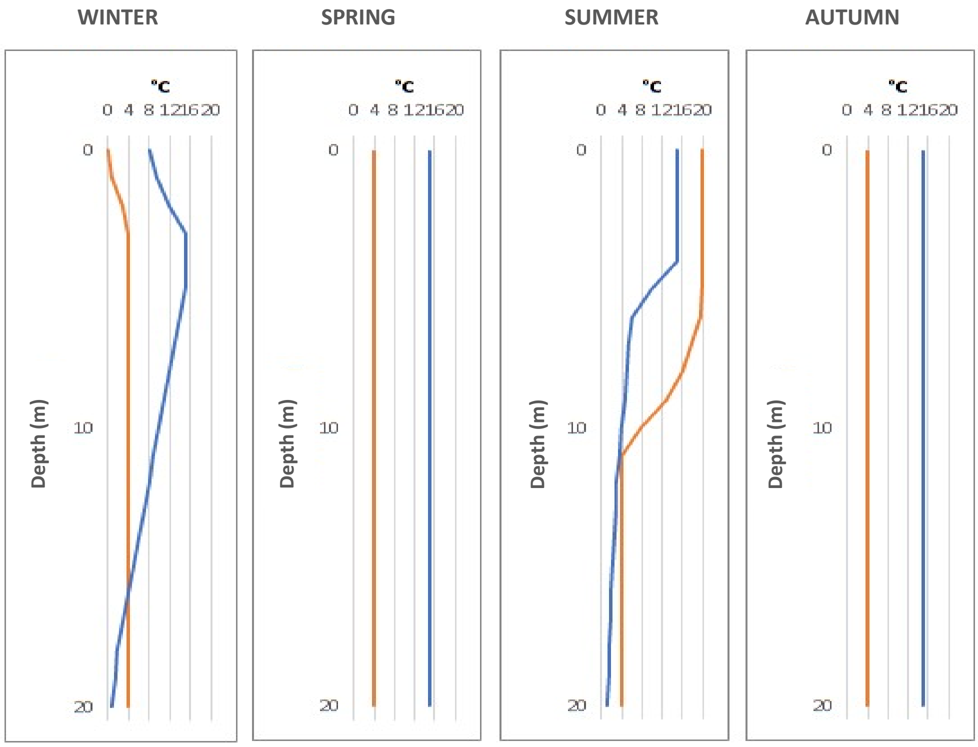


Figure 9. Qualitative variation of temperature (in orange) and dissolved oxygen (in blue) during the thermal cycle of a lake. Source: personal elaboration.

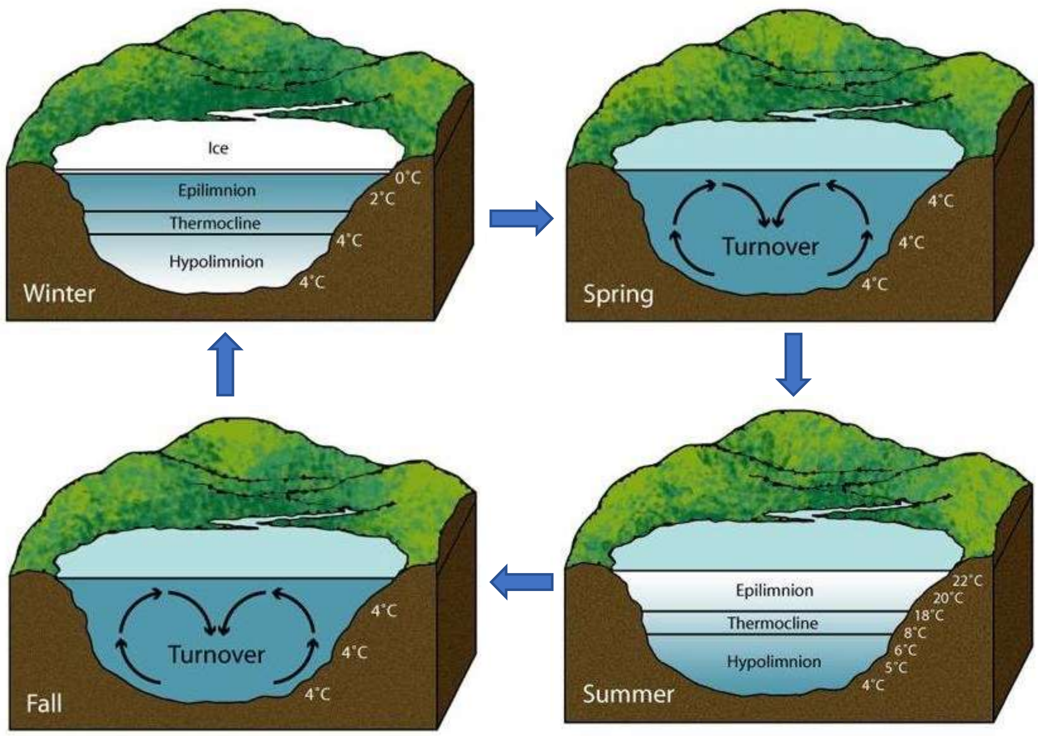


Figure 10. Representation of the thermal properties of lakes: each image corresponds to the thermal condition of the lake in a specific season. Source: personal notes.

1.3.5 Classification of lakes

Lakes can be classified based on the number of circulations carried out in a year (or turnover). Therefore, as the depth characteristics and climatic conditions to which they are subjected, or the thermal cycle explained, the lakes can be classified as:

1. *Amictic*: when full circulation never occurs, they are perpetually "sealed" by ice.
2. *Holomictic*: they have at least one phase of full circulation.
3. *Dimictic*: at least two phases of full circulation.
4. *Monomictic*: a single phase of full circulation (typical of sub-polar or sub-tropical lakes).
5. *Meromictic*: there is no phase of full and complete circulation and has a perennial stratification mainly due to the temperature profile and/or salts dissolved in the water, progressively increasing its density.
6. *Oligomictic*: they have irregular and non-constant circulation phases over the years.
7. *Polymictic*: they are generally too shallow lakes to develop a stratification during seasonal temperature variations; therefore, their waters are free to mix even if only by the action of the wind.

A lake that follows the alternation of characteristics over four seasons, typical of temperate zones, such as the one described in the previous paragraphs, is called *dimictic*, even if they may not present a real blanket of ice in winter. Alpine or high-altitude lakes very often fall within the category of *monomictic* lakes presenting the ice-free surface only for a short summer period, where the surface temperature exceeds 4 °C, but have only one period of isothermal energy and therefore a single full circulation period of water.

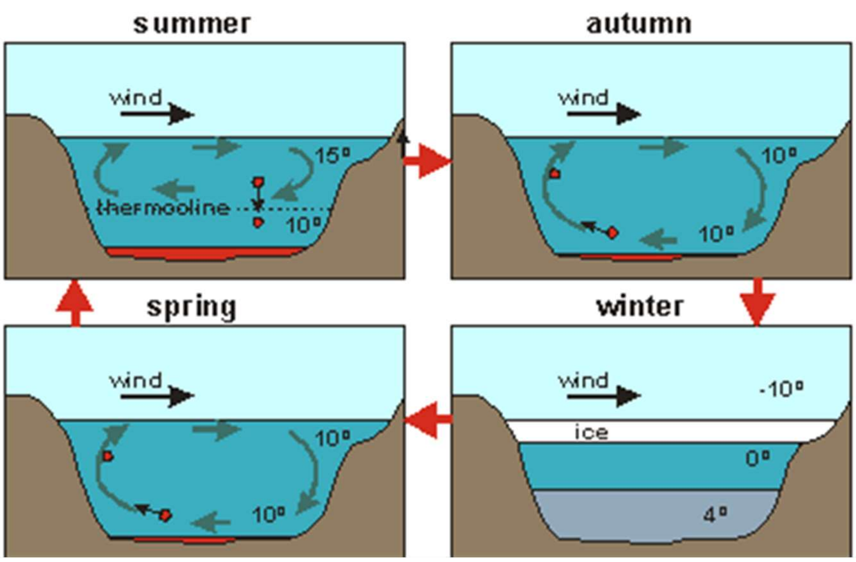


Figure 11. Representation of the flow of fresh water into a dimity lake: in autumn and spring the two full phases of circulation that characterize it are evident.

1.3.6 Effects of layering

The thermal cycle of a lake is influenced by climatic factors (rainfall and windiness) and morphological factors (depth and shape of the lake basin), but it depends mainly on latitude and altitude that directly influence the amount and intensity of solar radiation, *i.e.* the source of thermal energy, and the air temperature decrease in altitude due to the air pressure drop in altitude. During the warm season, a lake located in the temperate region sees all chemical reactions proceed more rapidly, as the temperature naturally increases the reaction kinetics within the epilimnion. On the contrary, the isolation of bottom waters from contact with the atmosphere, during the period of stratification, prevents the renewal of oxygen that is consumed by organisms and therefore water can become an anoxic environment. These conditions of absence of oxygen are always negative since it is the environmental conditions that can lead to the phenomenon of eutrophication. The substances contained in the anoxic hypolimnion layer can undergo a series of chemical and biological transformations very different from those that occur in the epilimnion. Chemical and thermal stratification limit vertical mixing in lakes and the diffusivity of this vortex is usually associated, at least, with thermocline: it is a function of the depth and morphology of the lake, the relationship between wind direction, solar insulation, the penetration of the light into the waters and other factors. It is worth mentioning the fact that the vertical dispersion coefficient in lakes is very low (values between $^{10-2}$ and 10^{+1} cm^2/s), much lower than that of rivers (especially when compared with the longitudinal dispersion coefficient larger than 4 OdM).

1.3.7 The colour

The temperature of the lakes is one of the factors that most influences their color. Below in Table 3 there is a small classification for the lakes of the area of interest.

No two lakes are the same: they all have distinct size, depth, and shape; forced by the soil in which they are located, by the rocks that are deposited. There are dark and deep lakes, there are those that exhibit and green waters and those of such transparency that it allows you to distinguish each of the pebbles that cover their bottom. Likewise, they present different colors because although pure water is colorless (pure is transparent): the color of lakes depends strictly on the refraction of light on the surface of the water, as well as on the chemical or mineral composition of the rock that forms its basin. For example, dissolved iron oxide provides a reddish color, the presence of algae or other plants that are inside it give rise to a cloudy and opaque green color. Thanks to these elements we can see the lakes showing different colors and modify them during the seasons, or during their ephemeral existence.

It should be borne in mind that the transparency of their waters also depends on the trophic level. These are different layers of nutrients that are distributed in lakes by the most related to the growth of organic matter.

Table 3. Type of glacial lakes in the Pyrenees. Source: Areito & Lopez, 2021.

Type of LAKE	Maximum surface temperature in summer (°C)	Duration of surface ice cover (mesi)	Ecosystem
Polar	5	≥ 10	Very small: neither vegetation nor fish are encountered in this type (unless they have been introduced by man).
Cold	9	> 8	The water is not very mineralized and very clear.
The Prairie	12	7	The dominant vegetation on the slopes is the alpine meadow.
Green	15	6,5	The vegetation blanket is greater than in other alpine lakes. The green color of the water is due to the organic matter that causes eutrophic of the waters.

An example: in general, in a lake of low level, few plants, few algae, few fish, flora and fauna generally decreased, and sandy bottom, the waters are transparent. On the contrary, when the levels and presence of all these components increase, fauna, flora, nutrients, organic matter, plankton growth, turbidity increases, and the waters become opaque. Hence the importance of maintaining the balance of ecosystems, very fragile and in which any alteration, however small, could turn into an important and drastic change in the lake ecosystem. There may be natural external alterations, such as the entry of minerals in suspension that could give it a whitish color, or it may be due to human action. It may be thought that their remote position, the altitude protects them from incursions of the latter type, but it emerges from a lot of literature that the lakes of the Pyrenees have undergone numerous impacts of an anthropic nature which have led to changes in their fragile ecosystem balances.

Therefore, the color of the waters of a lake is closely linked to the quality and quantity of suspended particles and molecules dissolved in its own water column. The transparency of the same is directly proportional to a lower presence of these elements and the consequent color will be tending to blue (whose wavelength penetrates to higher depths being dispersed by the same water molecules). For example, a turquoise color is a symptom of high concentrations of suspended inorganic material that causes a high dispersion of sunlight. In other cases, the abundant presence of organic compounds in the waters of a lake can give colors between yellow, orange, red or brown. A predominance of green color is a symptom of a high algal density and therefore, the presence of chlorophyll. The color of a lake is therefore a powerful indicator of the physical, chemical, and biological state of its waters and consequently of the health of its ecosystem.

Figure 12. Example of Green Lake: Tres Estanys 2425 m (Guingueta d'Àneu (CA), Pyrenees, Spain).

Figure 13. Example of a cold lake: Lago Blu, Val D'Ayas 2723 m (Champoluc (AO), Alps, Italy).

Most of the lakes found in the Pyrenees Mountain range, except for some lakes above 2500 m altitude considered alpine, are called cold lakes. They are in areas of wild and high clearings where the surface temperature of the water does not exceed 9 °C in summer and where the surface remains frozen for at least 8 months a year. They are transparent and poorly mineralized. Clearly its behaviors are clearly different from that of the lower lakes due mainly to climatic circumstances, altitude, and latitude.

Chapter 2
Location of the site under investigation

2.1 Characterization of the examined sites

The objective of this analysis is to characterize the temperature variation of some lakes located in the central-eastern Pyrenees and to perform a comparison of data and characteristics, as well as any observations related to significant changes in phenology.

Figure 14. Lake Mucrone in winter (Biella, Alps, Italy).

The lakes examined are mostly lakes that originated because of a glacial geological event: that is, the water collected inside depressions formed because of erosion by glacial tongues. They are surface lakes and therefore subject to normal variations in level deriving mostly from rainfall, or in general from meteoric inputs mainly concentrated in the autumn and winter season, or small underground springs. In this case, there are neither tributary rivers nor emissaries to the ones. Therefore, in the balance reported in Formula 1.1, the coefficient A is only given by precipitation flows – whether liquid or snowy – D and A_s can be considered zero, while the occurrence of underground infiltrations that depend mostly on the lithology and geology of the lake bottom cannot be excluded.

2.1.1 Glacial lakes

The type of lake examined here, glacial, or high mountain lakes, are ultimately the testimony of the Quaternary glaciations. Therefore, the lake occupies the cavity resulting from erosion by the glacier. From this point of view, glaciers represent the shaping agent that has left the most significant impact on the mountain landscape. In the topographic depressions generated by the under excavation of glaciers (basins) the waters of glacial, snow and meteoric melting are collected, configuring themselves as a sort of natural impluvium. The size of these lakes and their persistence is very variable, but the life of these lakes is not eternal and depends on the shape, depth, exposure and quantity and intensity of inflow and outflow of water, as well as the possible transport of sediment within them. In the three are no underground springs fed the volume of the basins.

Due to their location, glacial lakes are subject to a strong seasonal variability due to the high mountain climate. The latter forces aquatic organisms to complete their life cycle in the short summer season due to the ice sheet that covers the surface of the lake for most of the year. It can be more or less thick and, on whose surface, it is possible an accumulation of snow to generate a real physical "barrier" that prevents the passage of light towards the waters of the lake below. The conditions of absence of light lead to the cessation of photosynthetic processes by the algae and organisms present and consequent depletion of oxygen in the waters of the basin. From here we can say that somehow the lake system, in winter, "stops", while it reaches its maximum vitality in the summer season when, at the end of their metamorphosis, the insect larvae, grown on the bottom in spring, reach the surface.

The shape and size of the basin are very important: they generally have strong repercussions on the functioning of the ecosystems present there. The depth determines the presence of strong thermal, chemical, and light gradients that can favor or disadvantage the biotic colonizing species of the lake (mainly amphibians, macroinvertebrates, and insects, sometimes fish species due to man).

Figure 15. Estany de Saint Maurici, Parc National d'Aiguestorts de Sant Maurici, Pyrenees, Spain (18/02/2023).

2.1.2 The geology of the Pyrenees

The geology characterizing the Pyrenees Mountain range is mostly made up of granite and gneiss rocks, especially in the eastern part, while in the western part the reliefs are composed of granite with intercalations of limestone layers. Granite is a rock particularly resistant to erosion by atmospheric agents and very little fractured which results in minimal losses of the reservoirs.

2.2 Location

The Pyrenees are an excellent field of study for monitoring the effects of climate change on reservoirs, as they constitute a mountain region containing over 3000 lakes and ponds (Figure 16b).

The lakes and ponds identified and analyzed are a total of 11 and are located north of the autonomous community of Catalunya (Spain) and in particular located in the Pyrenees Mountain range, on the border with France, in the central-eastern part of the massif. They are partly located within the Parc Natural del'Alt Pirineu and partly within the Parc Nacional d'Aiguestorts I Estany de Sant Maurici: both are part of the areas included in the Natura 2000 Network, the main

European Union instrument for the conservation of biodiversity and the protection of ecosystems. In this regard, no threatened or protected species were involved during the temperature measurement. The instruments were therefore installed with the permission of the park managers.

The chosen series is between 42.68° and 42.53° N and between 1.33° W and 1.02° E (Figure 16a). The lakes are located in a range of altitudes between 2000 m and 2600 m above sea level. As far as the investigated surfaces are concerned, they are very varied: most of the lake areas are between 1 and 3 ha. It is possible to recognize from the photos in Table 3 a high spatial heterogeneity of the mountain areas that identify, each, local conditions that make each lake system unique and therefore the influences of external agents on its thermal parameters on a regional scale.

Table 3 summarizes the names of the lakes and their location in coordinates in DMS, the surface and an indicative photo of the basin. The coordinates are provided in Geographical unit – ETRS89.

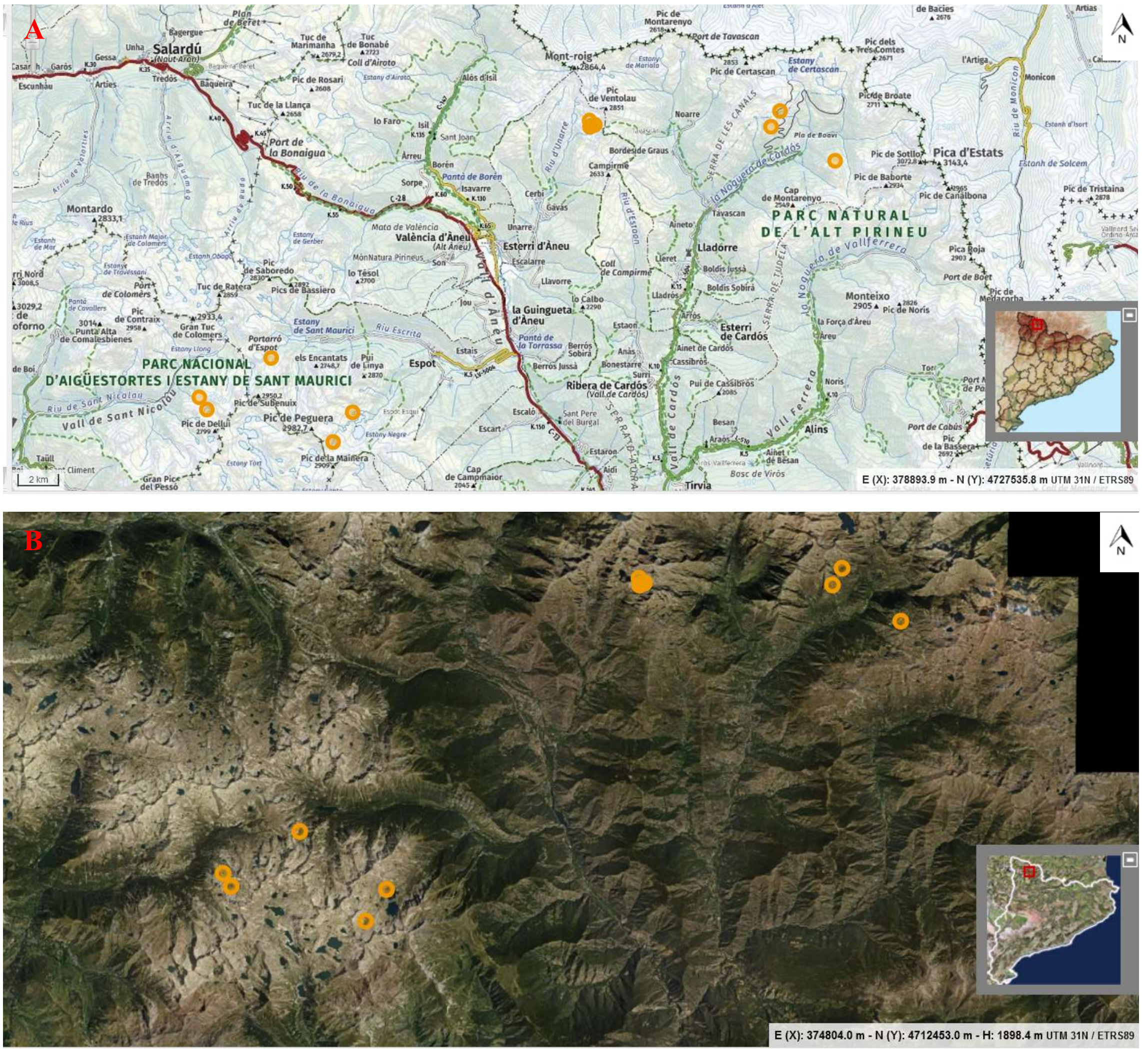


Figure 16. a) Topographic map of the investigated area. Survey points are marked in yellow. b) Orthophotos of the survey area. Points of interest are indicated in yellow. You can see from this map the large number of small lakes and ponds in this area. Source: ICGC.

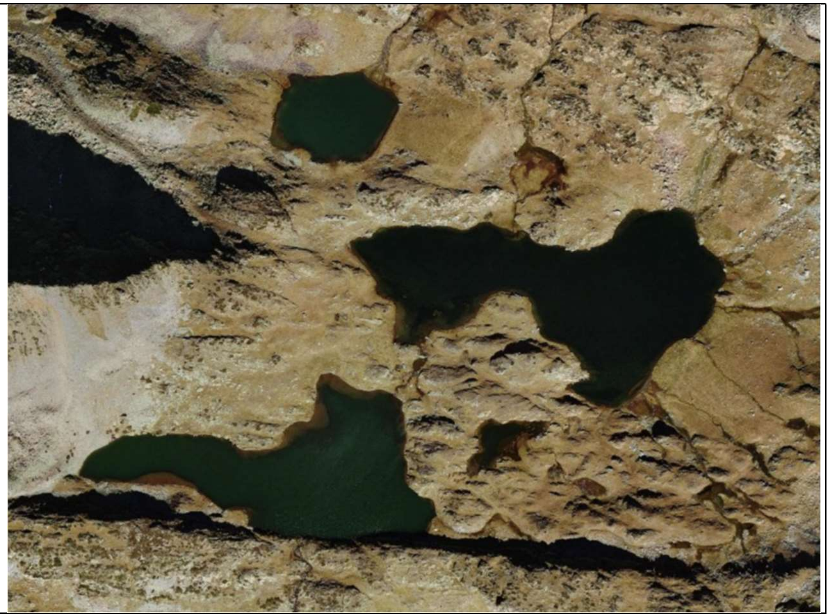
Table 4. Localization of lakes and ponds identified and analyzed. Source data: ICGC.

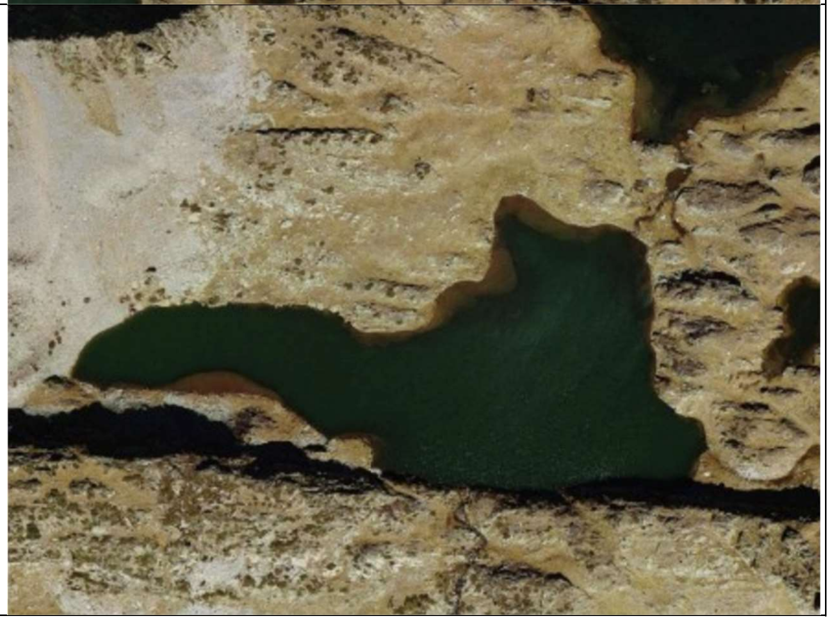
Num.	Lake Name	Longitude E	Latitude N	Altitude s.l.m (m)	Surface (ha)	Area of jurisdiction	Photo
1	Estany de la Cabana	1.038981	42.548201	2376	0.6	Municipis: Espot Comarques: Pallars Sobirà Provincia: Lleida, Catalunya (ES)	
2	Estany del Cap de Port	1.026515	42.533824	2521	7.4	Municipis: Espot Comarques: Pallars Sobirà Provincia: Lleida, Catalunya (ES)	

3	Estany Closell	1.295021	42.682824	2074	0.5	Municipis: Lladorre. Comarques: Pallars Sobirà. Provincia: Lleida, Catalunya (ES)	
4	Estanyet de Dellui mig	0.947807	42.547988	2349	1.1	Municipis: la Vall de Boí. Comarques: Alta Ribagorça. Provincia: Lleida, Catalunya (ES)	

5	Estany de Dellui Nord	0.943391	42.553213	2314	0.3	Municipis: la Vall de Boí. Comarques: Alta Ribagorça. Provincia: Lleida, Catalunya (ES)	
6	Estany de Naorte	1.300001	42.689755	2150	3.9	Municipis: Lladorre. Comarques: Pallars Sobirà. Provincia: Lleida, Catalunya (ES)	

7	Estany de Rovinets	1.334530	42.667628	2223	0.4	Municipis: Lladorre. Comarques: Pallars Sobirà. Provincia: Lleida, Catalunya (ES)	
8	Estany de Subenuix	0.987445	42.571799	2195	2.6	Municipis: Espot Comarques: Pallars Sobirà Provincia: Lleida, Catalunya (ES)	

	Tres Estanys					Municipis: Guingueta d'Àneu. Comarques: Pallars Sobirà. Provincia: Lleida, Catalunya (ES)	
9	Tres Estanys Baix	1.180259	42.678388	2344	2.8		

10	Tres Estanys Mig	1.181361	42.680783	2411	3.7		
11	Tres Estanys Superior	1.184388	42.682452	2413	0.8		

Chapter 3
Data Collection and Methods

3.1 Data collection

The study of the temporal evolution of the temperature of the waters of the lakes is allowed thanks to the installation of Minilog thermistors with datalogger inside the ponds. These Minilog thermistors with Datalogger are of the Vemco minilog-T or Hobo UA-002-64 type and were initially installed at a depth of 1.5 m and separated from the bottom of the lake using a fishing rod.

A thermistor is a sensor that is used to detect the slightest temperature change very precisely through a large resistive variation of a sintered semiconductor material. Generally, these devices have negative temperature coefficients – NTC – *i.e.* as the temperature increases, a decrease in resistance is caused (see Annex I for the data sheet). Data on the water temperatures of these lakes were collected by reading the thermistors installed in them (Figure 17).

Figure 17. Schematization of the data collection and storage process.

Data availability, in general, runs from 2015 to July 2022, although some ponds such as Closell have a relatively longer and more complete series that began in 2010. Water temperature measurements were taken at 1.5-hour intervals. Already since 2015 in some lakes the temperature record has increased to 1 record every hour. Since the summer of 2019, thermistor chains have been installed in all lakes consisting of 3 or 4 of these – depending on the depth of the lake –

positioned vertically in the water column. This allows us to have temperature data at different depths for the years 2019-2022 of all the lakes investigated: it allows us to accurately examine the cyclical evolution of mountain lakes, as described in Section 1.3.4. Overall, data sets are available that make up 8 years of recording of the summer temperatures of the waters of each of the lakes presented in Table 4.

Thermistors are also able to measure the intensity of light radiation: the latter reaches the surface of the lake to varying degrees depending on the geographical location of the lake, the altitude and the transparency of the atmosphere. When it comes into contact with water, it is partly reflected and partly absorbed by the body of water heating it: almost all ultraviolet radiation is retained in the first meter of thickness of water (according to an exponential law of radiation penetration). It should be noted that in this context, the light radiation considered effective, which is the function of the variation of the water temperature, is only the diurnal solar one since the lunar nocturnal radiation is completely negligible (Welch, 1952). This can also be guessed from the absence of light radiation recorded by these sensors during the night hours. These series, unlike the temperature ones, are incomplete and very noisy; Therefore, they will not be considered here except to reconstruct small sets of data or prove the correctness of others.

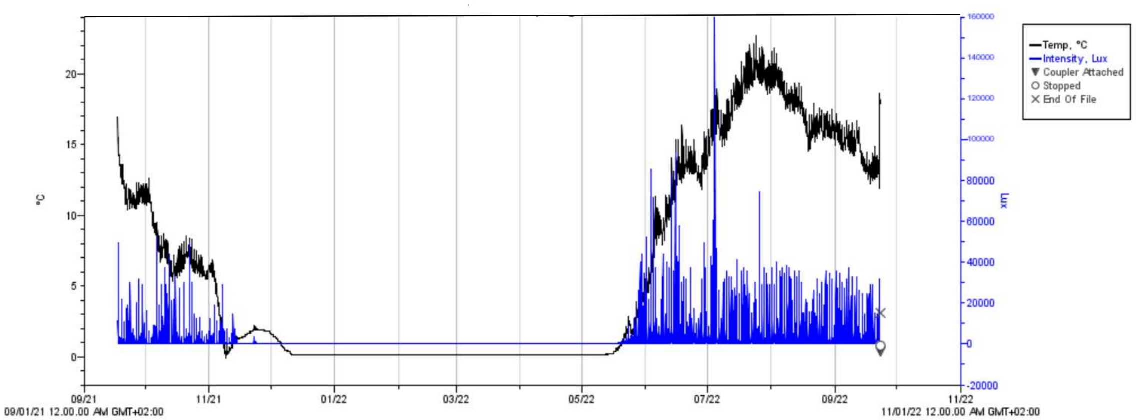


Figure 18. Example of raw data obtained directly from the thermistor and integrated with the appropriate software for the Estany Tres Estany Mig (Pyrenees, Spain).

The instrument has an accuracy of ±0.1℃ and records the temperature continuously throughout the year and is replaced, when possible, before the battery runs out (normally in July or September).

A first observation on the quality of the monitored data is due. The data collected presents some missing data, as summarized in Table 5, but it has been chosen to reconstruct only small series of data in order not manipulate it excessively. Where the data were reconstructed, linear regression models were developed using, where present, thermistor chains data – for the years after 2019 and clearly very well correlated because they are composed of thermometers belonging to the same lake – or temperature records of nearby lakes verifying the presence of a significant correlation between these also in terms of altitude and basin size (carried out only for short time periods missing < 2 months).

Table 5. Summary diagram of data availability for analyzed lakes.

Name Estany	Year of measurement start	Significant lack of data (>3 years)	Number of years monitored	Numbers of years available
Cabana	2015	NO	8	7
Cap del Port	2016	NO	7	6
Closell	2010	YES	13	10
Dellui Mig	2015	NO	8	6
Dellui Nord	2014	NO	9	7
Naorte	2014	NO	9	7
Rovinets	2015	NO	8	5
Subenuix	2014	YES	9	4
Tres Estanys Baix	2015	YES	8	7
Tres Estanys Mig	2016	YES	7	5
Tres Estanys Superior	2015	NO	8	6

The monitoring and acquisition of data is continuous and is affected by the presence of numerous data holes caused by the breakage or malfunction of the thermistor or by the loss of computer archives over the years, and at last the Covid-19 pandemic period that which made it difficult to update and the collect data. The measurements were carried out by CEAB researchers.

3.2 Initial hypotheses: the concept of system

To study a physical environment, given its complexity, it is necessary to place boundary conditions to allow a simple, unitary, but at the same time complete description.

In this context, we choose to use the theory of systems that allows the schematization of the problem and defines a "*system*" as a set of elements, conditions and functions that describe the relationship between them and with the environment: in this way it is possible to frame the cause-effect relationships in a unitary way. From this point of view, natural systems are the most complex due to the large number of parameters necessary to describe them.

A lake environment, such as the one examined, is subject to numerous interactions with the external environment and therefore analyzing each of them as an isolated system allows us to extrapolate from a *continuum* singular situations, isolating effects and interactions not contemplated in the analysis models and circumscribed possibly extendable in terms of results to the entire area.

3.3 Dependence of surface water temperature on atmospheric temperature

The fundamental interaction that must be kept in mind in this analysis is that atmospheric temperature strongly affects the temperature of the lake surface. As mentioned, solar radiation and atmospheric temperature represent the two most important meteorological elements for the analysis of the evolution of the state of a lake basin. In fact, if on the one hand they contribute to the definition of the caloric balance of the system, on the other they are decisive in defining the local climatic characteristics.

To demonstrate this statistical dependence, it was decided to use a linear regression model by coupling the values of surface water temperatures with the average air temperature value over the same period. It emerges that considering a single grouping, the correlation between the two variables turns out to be equal to 0.75 and is judged in this context not very significant. Therefore, you choose to divide the data and group them into 3 distinct phases of the seasonality of a lake system, applying the method to monthly temperature averages data:

1. May - August: which correspond to the phase of water heating.
2. September - December: which corresponds to the cooling phase of the water.
3. January - April: corresponding to the limnological winter and the presence of the seasonal ice cover.

The air temperature data were obtained from the weather station closest to the group of lakes analyzed: Lac Redon is in the Val d'Aran in the municipality of Vielha e Mijaran Lat. 42.64 Long. 0.78.

The linear correlation in the cooling and heating conditions of the lake waters – cases 1 and 2 – is very strong, while it is completely absent during the limnological winter period: this is due to the presence of the ice cover that forms in all these lakes during the winter period which therefore limits the direct interaction between the air and the waters of the lake. Figures 20 and 21 show the correlations just described and performed for 4 different lakes to confirm the representativeness of the meteorological station and the actual relationship between the variables (R^2 is never less than 0.87).

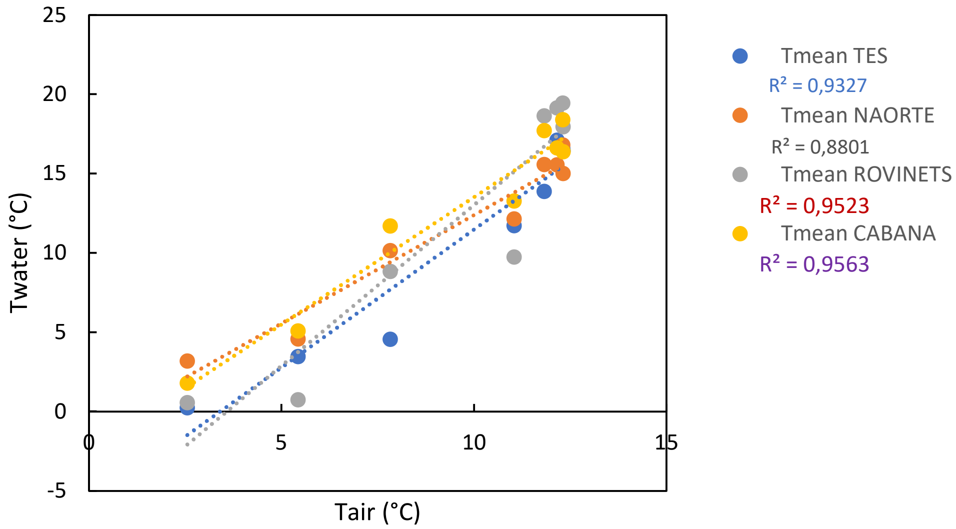


Figure 19. Linear correlation between the air temperature and that of the waters of some lakes analyzed for the heating period: May - August.

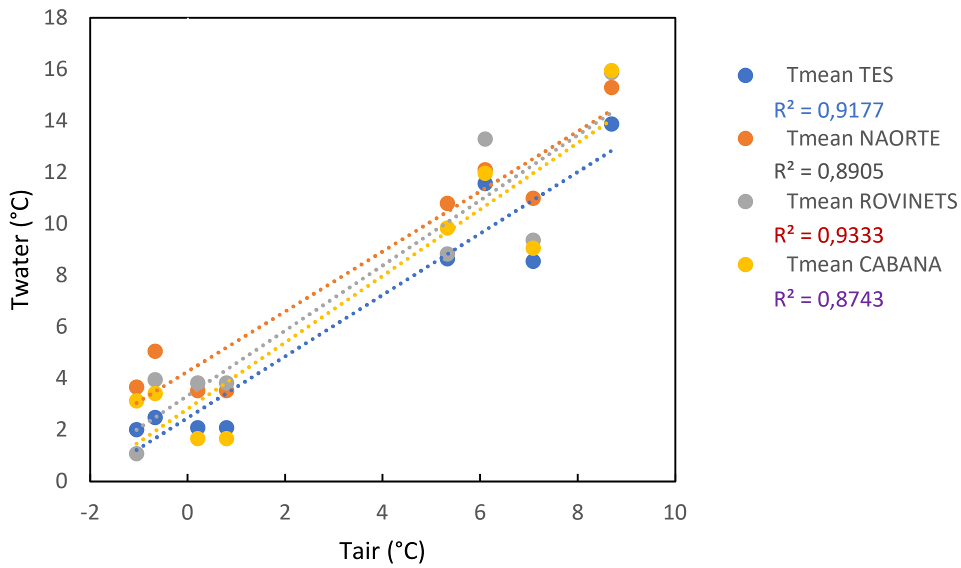


Figure 20. Linear correlation between the air temperature and that of the waters of some lakes analyzed for the cooling period: September - December.

Clearly, it is also clear that lakes with water temperature better correlated with those of the air in contact are also relatively closer to the measuring weather station, located at the same altitude (2,247 m).

3.4 Analyzed variables

The variables of ice-on (freezing date) and ice-off (melting date) were analyzed, which are the main references for the evaluation of snow cover with respect to the temperature data series. The period between these two parameters is characterized by an almost constant temperature – in all the thermometers installed where the chains are present – but hardly below zero. These dates have been obtained directly from the graph of the diary trend of temperatures where this same variable, generally after the evident period of autumn presents a decrease in temperature and an important slope in the graph, begins to stabilize. The dates were calculated as an ordinal date and the values inherent in the number of days with the presence of ice cover on the surface of the lake were calculated as the difference between these two variables (ice-off minus ice-on).

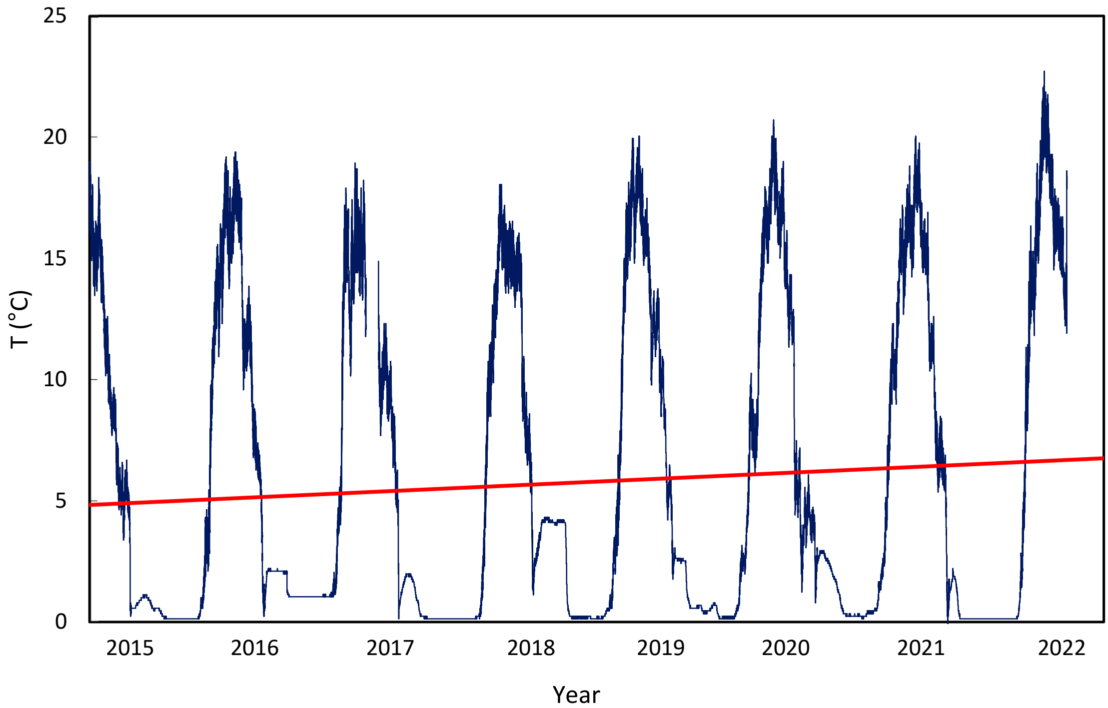


Figure 21. Graph showing the interannual variability of the average daily surface water temperature measured at 1m depth in Lake Tres Estanys Superior (Pyrenees, Spain). In red the temperature trend line.

The average, maximum and minimum daily temperature parameters were then calculated (merging the temperature measurements collected in a day), then purely statistical parameters such as standard deviation and variance, as well as the oscillation on the maximum temperature (T max) and the amplitude of the thermal difference between the T_{max} and the minimum daily temperature (T_{min}). These parameters are also calculated annually.

A fundamental parameter of phenological analysis, *i.e.* the classification and recording of significant events in the development of organisms within an ecosystem, is the calculation of Degree Days (DD).

3.4.1 DD and ADD calculation

It is one of the most widely used mathematical forms to, as anticipated in Section 3.4, monitor the quality of the environment, and corresponds to the thermal accumulation necessary for the development of an animal or plant organism.

The Degree-Day is defined as the number of degrees of temperature above a certain basic threshold (T_T) that varies according to the species examined. The "temperature *threshold"* is a lower temperature limit that represents, for the species, a level of growth equal to zero. This parameter is calculated starting from maximum and minimum daily temperatures giving rise to a sinusoidal function (*single-sine* method) in approximation of the curve representing the daily thermal cycle.

The DD is calculated according to the following formulas (Baskerville and Emin 1969) depending on whether the threshold temperature (T_T) is higher or lower than the minimum temperature (T_{min}). So:

$$T_{min} > T_T \rightarrow DD = \frac{T_{max}+T_{min}}{2} - T_T \qquad (3.1)$$

$$T_{min} < T_T < T_{max} \rightarrow DD = \frac{1}{\pi}\left[\left(\frac{T_{max}+T_{min}}{2} - T_T\right)\left(\frac{\pi}{2} - \theta_1\right)\right] + Acos(\theta_1) \qquad (3.2)$$

Where:

$$\theta_1 = arcsin\left(T_T - \frac{T_{max}+T_{min}}{2}\right) + A \qquad (3.3)$$

$$A = \frac{T_{max}-T_{min}}{2} \qquad (3.4)$$

If T_{max} it is lower than the temperature T_T , the return value is zero.

As can be seen in the formulas just proposed, if the average daily temperature is higher than the minimum for the same time frame, then the DD is calculated as a simple average between the maximum and minimum temperature, minus the threshold temperature. In this way, it is understandable how the contributions of DD are gradually increasing as the seasonality progresses: from winter, practically absent, to the summer season, greater contributions in accordance with the phenology of the system.

For both day clearance calculation formulations, a threshold was used first below 4 °C and then 7,6 °C. These are threshold temperatures -T_T horizontal threshold cut-off techniques (Baskerville and Emin 1969) - commonly used and representative of many amphibian species. In particular, the measurement of the Degree-Day (DD) measures the accumulation of heat and in the absence of extreme external conditions (such as drought), allows to monitor the state of growth of fauna and flora that is strongly influenced by the temperature of the environment. In fact, for many species of plants and insects (as well as amphibians), their development depends on specific amounts of heat that are distributed cyclically during the growing season, regardless of the temperature between one year and another.

Once the daily DD has been calculated, the ADD can be calculated for each water body and for each year available in the data. The ADD represents the cumulative of DD, or the temperature integrated over time beyond a determined threshold, and it is this parameter that is properly used for the evaluation of the life phases of the fauna, as well as to estimate the thermal stress in ecosystems. The ADD was calculated for ice-free periods, defined as the time periods between the ice-on and ice-off dates, therefore, including the summer season of each year. ADD is measured from the winter minimum.

$$ADD = \int_{T_T}^{T_{max}} T\,dt = \sum_{i=ice-on}^{ice-off} DD \qquad (3.5)$$

3.5 Data analysis

For the analysis, the ADD values for each year - for which sufficient data were available for this calculation to be representative - were compared for the individual lake. Priority will be given T_T to parity at 7.6 °C.

Only the data of years that were within the average of ADD for the specific lake and with the presence of data at least equal to 90% of the summer season were considered significant. In some cases, it was possible to reconstruct the data series through linear correlations between the temperatures of nearby lakes and similar in size accepting only R^2 values greater than 0.96. The procedure is clearly affected by errors of approximation, but in some cases necessary to preserve the significance of the point analyzed.

The purpose of the survey, as mentioned, is to verify whether 2022 was really an exceptional year in accordance with what was reported by weather temperatures and the high degree of drought. To show this, we evaluated the degree of variation present in each site, we generated Figure 23 which shows the percentage of deviation of the value of ADD 7.6 between the years analyzed and the year 2022.

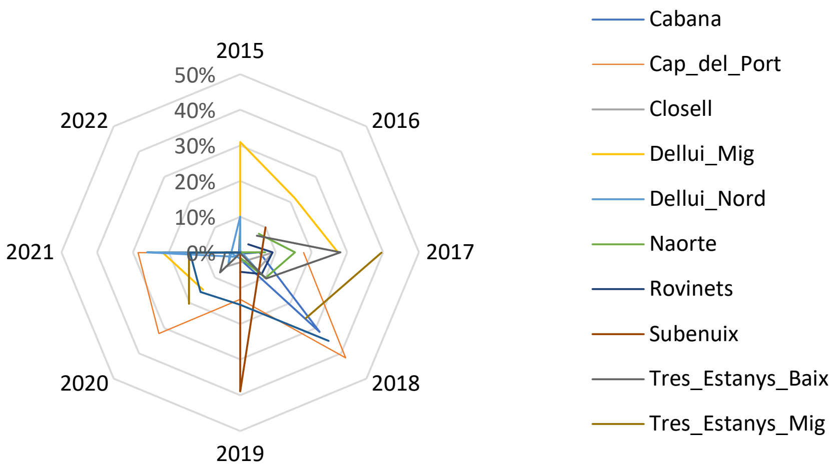


Figure 22. Diagram showing the percentage variability between the years analyzed from (2015 to 2021) compared to the year considered "exceptional" 2022.

Chapter 4
Discussion of results

4.1 Evidence

At first, the relationships between the variation of the surface temperature of the water of the lakes and the main climatic factors – air temperature and precipitation – recorded by the nearest meteorological station and located in a barycentric position between the two groups of lakes analyzed were compared. The graph in Figure 24 shows these relationships: except for the first period where clearly, at these altitudes, the air temperature is below zero with daily variability, the variability of water temperature is almost zero due to the formation of the surface ice cover. The latter is recorded as a common constant for all the years examined and for all lakes. In summer the two curves are much more similar in terms of trend except for the daily oscillation which, given the thermal properties of the water, are more limited in the case of the temperature of the lake. The interaction between rain events and water temperature is interesting: in the presence of significant precipitation there is a drop in water temperature, especially in the case of rainy events distributed over several consecutive days, while the maximum temperature is associated with the minimum rainfall. This trend was recorded for all the lakes observed (Figure 25) and this also allows us to consider this weather station as a database - by virtue of the linear relationship between air temperature and lake water - and control for the reconstruction of some missing data sets. Furthermore, it has been shown that, except for minimal local effects, the climate and consequently the air temperature are – at the same altitude – similar throughout the Pyrenees area (Sabas, et al., 2021).

Therefore, a weather station located at one point is sufficient to record the climate of the entire area and to be able to consider valid the approximations deriving from relations with atmospheric conditions.

As can be seen from the graph shown above in Figure 22, there is an increasing trend in temperature (IPPC, 2021), *i.e.* an increase in average temperature over the years. This trend is between 0.5 and 3.4 °C regardless of the altitude at which the tin is located (see Table 6).

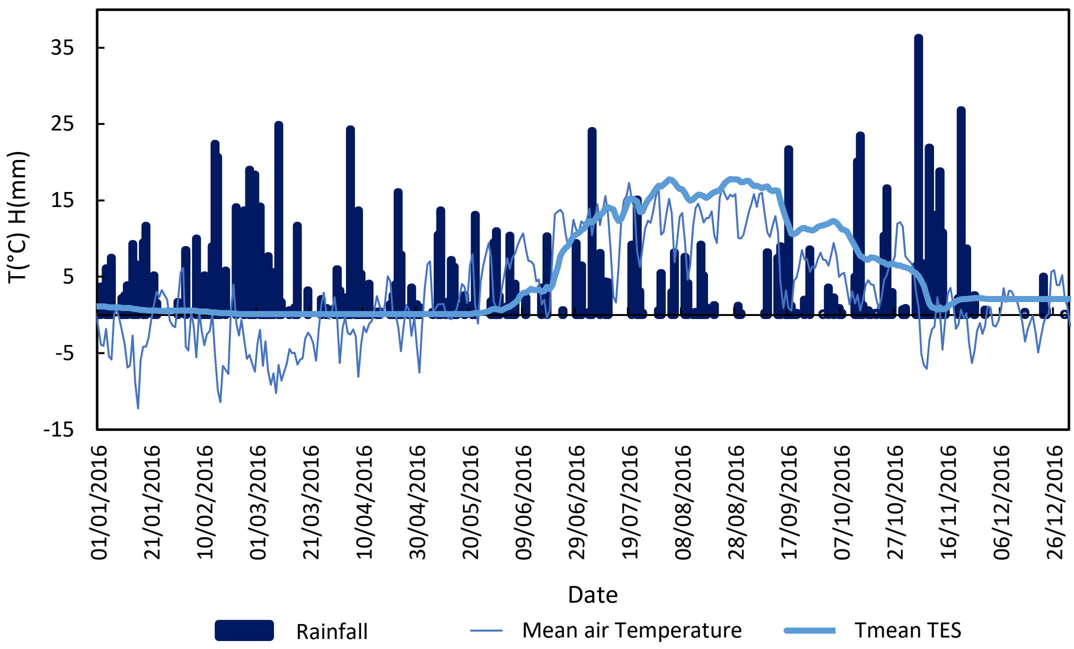


Figure 23. Graph showing the annual trend of air temperature (Redo weather station), surface water of Lake Tres Estanys Superior (Pyrenees, Spain) and rainfall for the year 2016.

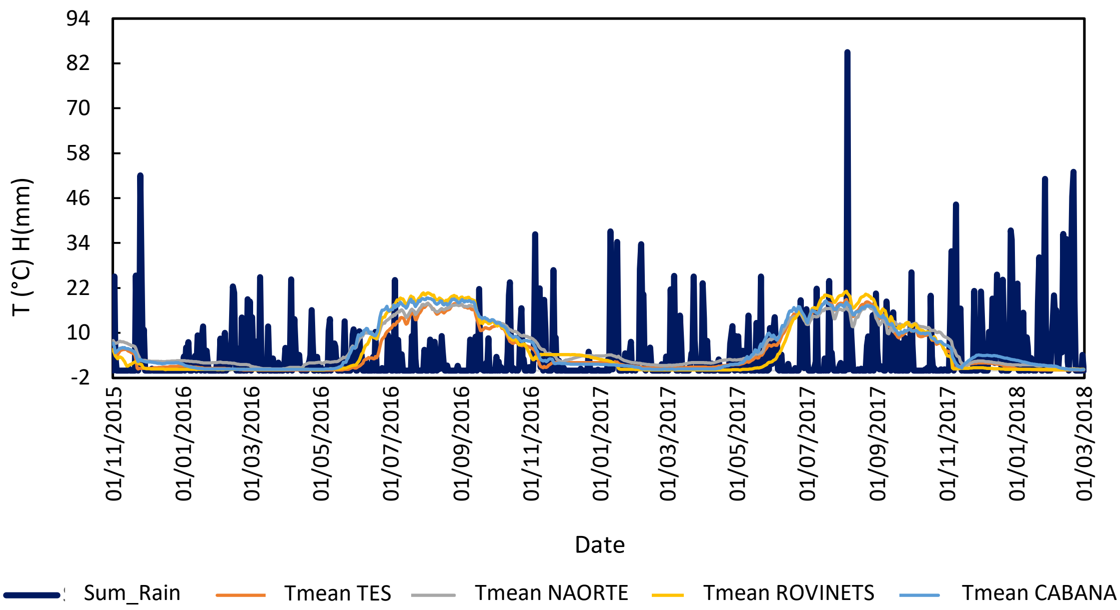


Figure 24. Graph showing the annual trend of air temperature (Redo weather station), surface water of 4 lakes analyzed (Pyrenees, Spain) and rainfall for the year 2016.

Table 6. Average and maximum temperature data, percentage rate for the period 2015-2022.

LAKE	TMEAN (°C)	TMAX (°C)	YEAR TMAX	INCREASE OF T (°C)	RATE OF GROWTH
CABANA	11,1	22,8	2022	3,4	6%
CAP DEL PORT	12,7	21,7	2022	1,8	5%
CLOSELL	13,3	25,6	2017	0,5	1%
DELLUI MIG *	11,1	21,7	2022	5,6	10%
DELLUI NORD	12,7	21,5	2022	2,4	4%
NAORTE	12,3	22,3	2022	2	3%
ROVINETS	13,9	24,2	2022	2,2	4%
SUBENUIX	10,8	23,3	2017	2	4%
TRESESTANYBAIX	12,9	21,3	2020	2	4%
TRESESTANYMIG *	12,6	22,6	2022	4,9	13%
TRESESTANYSUP	12,0	22,7	2022	2	4%
MEAN	**12,3**	**22,7**		**2,6**	5%
TAIR	3,3	19,9		0,4	0,5%

The average temperature between the lakes considered is about 12.4 ° C (±1 °C), calculated as the average of temperatures between the dates of ice-off and ice-on, considering in this way the only summer period decidedly more significant also from the point of view of measurements[6]. The average maximum temperatures recorded is 22.7 °C. Most of the maximum temperatures in the period considered were recorded in the year 2022, except for Lake Closell and Subenuix to which the maximum recorded is associated with the year 2017. Overall, the average temperature increase between 2015 and 2022 was 2.6 °C (that of air over the same period was 0.4 °C).

The number of days in which the water temperature, for each lake, exceeded the threshold of 20 °C was also calculated: for most of them the year that recorded the most records of this type was 2022. Another important year, from this point of view, was 2016 which was, according to the available data, as the second warmest year in the series analyzed.

It was decided to calculate an annual growth rate for temperatures in the number of years considered for each of them. In particular, the *Compound Annual Growth Rate* (CAGR) was used, which allows to generalize the average exponential growth rate over a time horizon (≥ 2 years). The average annual temperature growth rate was 4%. Some of the largest percentages belong to the most numerically manipulated lakes: these outliers warn us from the point of view of interpreting the results for these data sets and are not considered for this calculation.

Below are the graphs related to the available data series relating to the surface temperature of the waters of the analyzed lakes: the total of the lakes is divided into 3 groups according to the altitude. Figure 26 shows the interannual variation of air temperature and below, for comparison, the interannual variability of the water temperature of two lakes positioned at the extreme (maximum and minimum) altitudes examined – respectively Estany Cap del Port, 2,521 m and Estany de Closell, 2,074 m. The difference in temperatures reached between the latter two is evident from the vertical deviation of the two curves[**]. In addition, it is possible to observe the freezing point of the surface, just after the long autumn mixing, coinciding quite between the two lakes, while the ice-off date and the summer compound are anticipated in the case of Lake Closell, or the lake at lower altitude. This means that precipitation – snowfall – is homogeneous on the territory even though the two lakes are in two different valleys, but above all that the difference in air temperature due to altitude (about 1 °C every 150 m, in this case about 3 °C) are fundamental factors to determine the moment of melting of the seasonal snow cover. The deviation of the curves is minimal in terms of ice-off date in the years that appeared warmest, namely for 2016 and 2022.

The air temperature graph corresponds to the automatic weather station located at Lac Redon (in the middle of the survey area). The air temperature graph in Figure 25 presents, in correspondence with the years 2020 and 2022.

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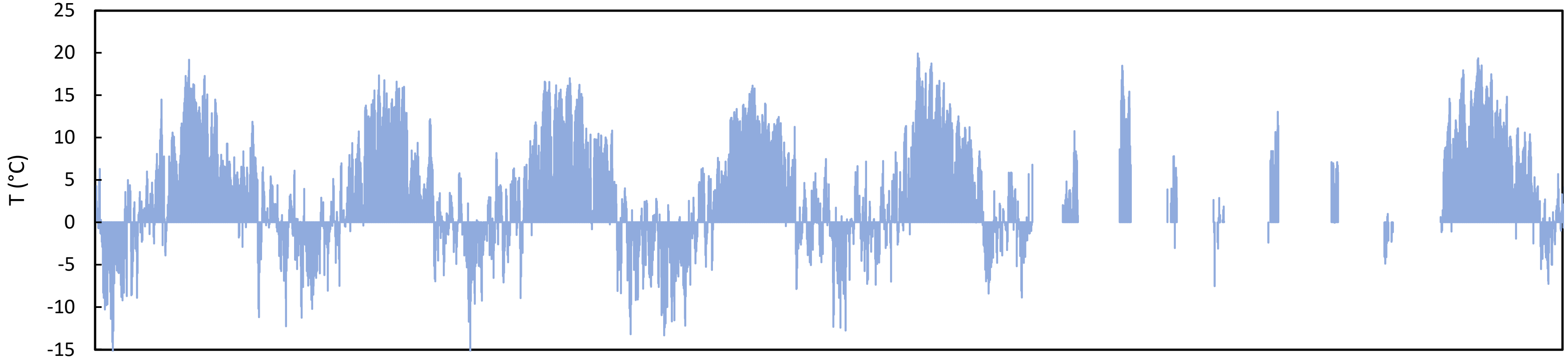
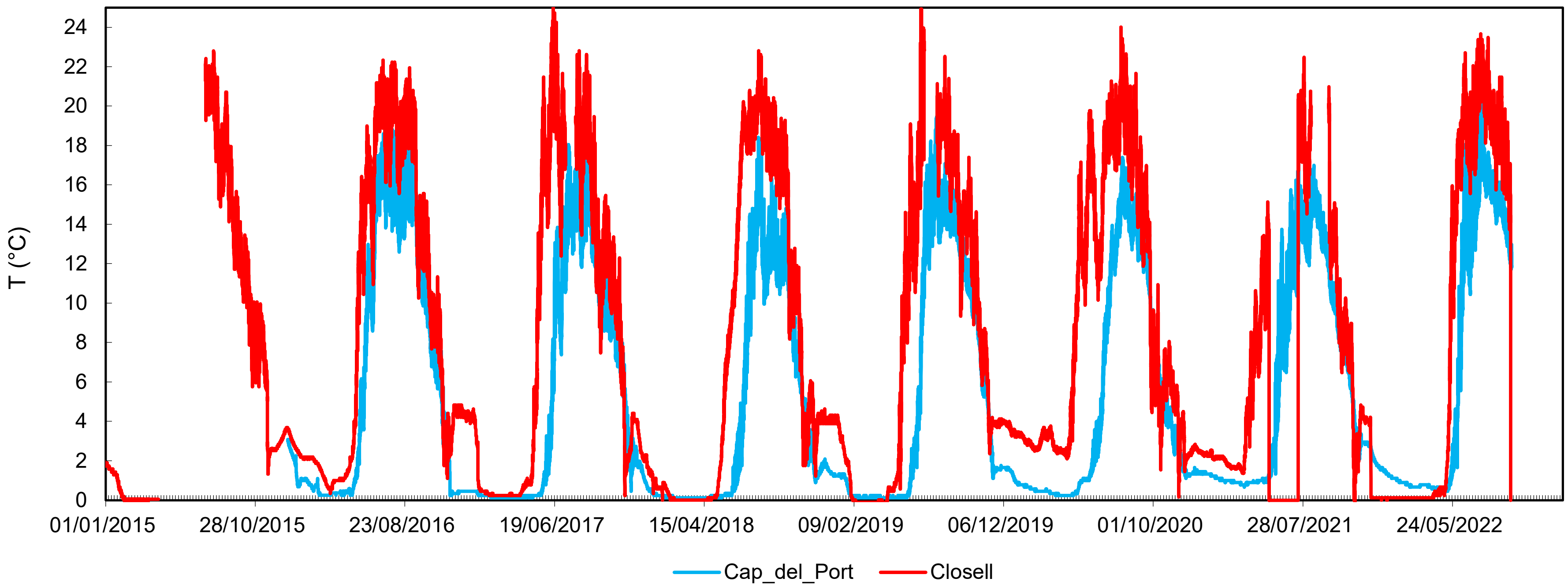
[*] Estany Dellui Nord and Tres Estany Mig present several consequential data in the series insufficient to be able to accurately calculate the growth rate (which clearly turns out to be larger than the other lakes for the same years considered); however, it was decided to insert the data in the table for completeness of the discussion.

[**] Many times the temperature measurements of the period related to the limnological winter are distorted in relation to the variable thickness of the ice cover, which can also arrive, in some cases, even to include the first thermometer of the thermistor chain depending on its position with respect to the free surface that differs from lake to lake. Therefore, negative values (< 0°C) may also be present, but discarding these values does not affect the result of the calculated parameters (T_{max}, T_{min}, T_{mean}, DD and ADD).

Figure 25. Graphs showing the trend of the air temperature (above), below the temperature series for the lake with maximum altitude (Estany Cap del Port, 2,521 m) and minimum (Estany de Closell, 2,074 m).





4.3 Evolution of the value of ADD

The graph in Figure 27 shows the trend of the degree-day accumulation function calculated for each lake over the time frame considered. Also, in this case it highlights an increasing trend for each lake and a similarity between the values found for the year 2022 and those of the year 2016. While in 2018 there is a minimum index of a year relatively colder than the others analyzed for many lakes.

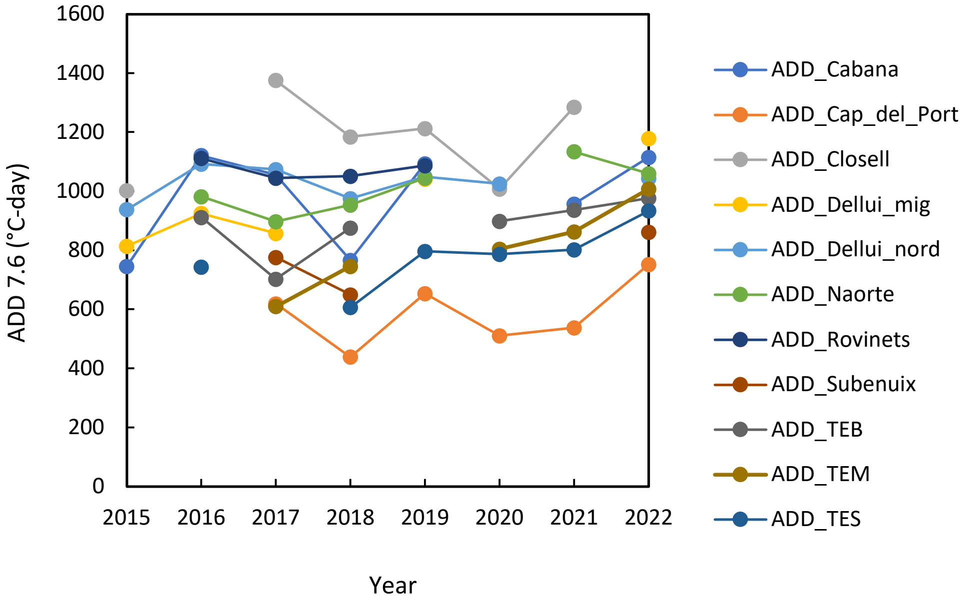


Figure 26. Change of the parameter ADD for each lake analyzed over time 2016-2022.

More significant, in this sense, are the set of graphs shown in Annex II: in Figure 28 one of them is reported as an example.

In these graphs, only the curves of the years have been shown containing enough data to be included in the ADD-trend for each individual lake. In addition, the data were normalized by placing the "0" at the date of melting of the ice cover (normally different for each year), to facilitate the comparison between the curves for the same lake by normalization of the data, but also for the same year, but different lakes. From the normalized curves it is possible to see that the start of energy storage is earlier in 2022 than in other years. It should be borne in mind in the observation of this graph that the calculation for the year 2022 is not complete as the data are available until July (date of the last collection campaign). The way the DD sinusoidal curve is constructed, this means that the temperature has positioned itself above the threshold 7.6 ° C earlier than in other years, indicating an early warming of the climate. According to this observation, the years 2021 and 2019 also anticipated the accumulation of °C-day, confirming, in a certain sense, the progressive increase in temperatures. We want to observe how the final values of ADD for these two years were still significantly lower than those of 2022 but attributing the second maximum to the year 2021 where present in the data series. It can be observed that 2016, in almost all the lakes considered, represented an important maximum of the value of ADD thus confirming, through the trend like 2022, to be the second warmest year of the analyzed series.

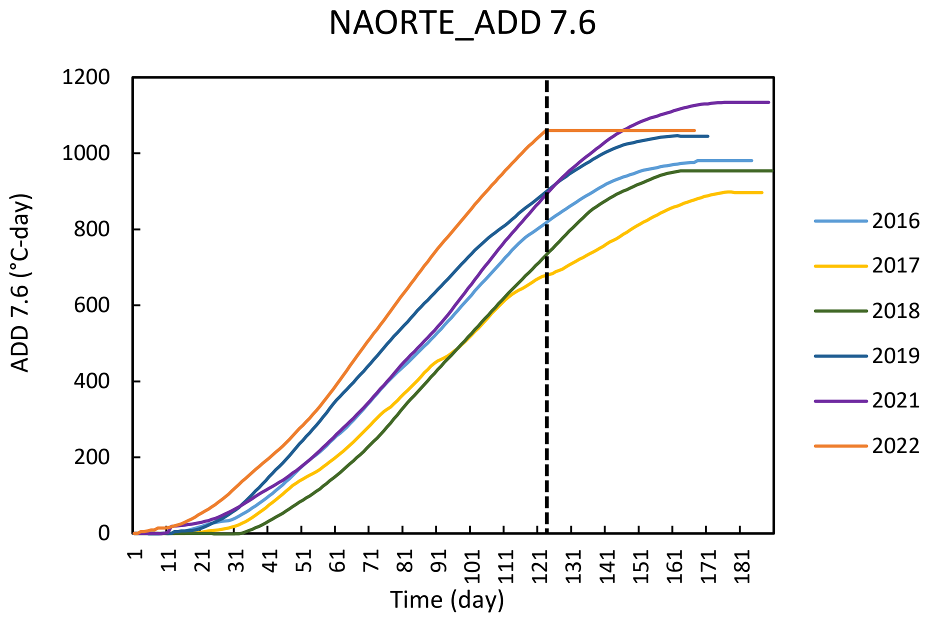


Figure 27. Graph ADD 7.6 made for the annual data series for each lake. In dashed black we indicate the point up to which 2022 data are available.

The coldest year seems to have been 2017 presenting a minimum of ADD in almost all the lakes analyzed between the years 2016-2022, where the onset of the accumulation of °C-day is also very delayed, compared to 2022.

It is evident that the final cumulative values between one year and another enjoy a certain variability that does not show a uniform trend or a directly increasing trend over the years. The position of the bending represents the point at which the temperature – generally towards the end of August – begins to decrease and with it the contribution of the DD (degrees-day) leading to a reversal of the trend of the curve until its stabilization in correspondence with a zero contribution of DD (limnological winter); Finally, the value stabilizes on a horizontal asymptote. It is evident that the greatest contribution to the final ADD value is given by the DD relative to summer temperatures: the higher the maximum temperature, the greater the value of degrees-day obtained.

It should be noted that 2022 (whose temperature measurements for the same year are incomplete and stop in July) proved to be an exceptional year from the point of view of energy storage. The curve is clearly shifted towards higher values of ADD compared to previous years: the difference with the nearest years – 2021 and 2019 – is equal to about 160 degrees-day. This deviation is recorded in all the lakes analyzed but presenting with different magnitudes depending on the site.

4.4 Variability of the ADD value

The variability was studied through the calculation of the range (difference between maximum and minimum) of the annual ADD values obtained. Values very distant from the average were excluded because they were not very significant and probably subject to data shortages, and it was also decided not to consider the values obtained from data reconstructions to have a picture as faithful as possible to the real water temperature data of the systems. These limitations have led to obtain a matrix of ADD values and corresponding range (Figure 29) evaluated between the years (INTER-annual) present for the same lake (INTRA- lake) and between distinct lakes, but with reference to the same year (INTER-lake). The overall matrix is given in Annex III.

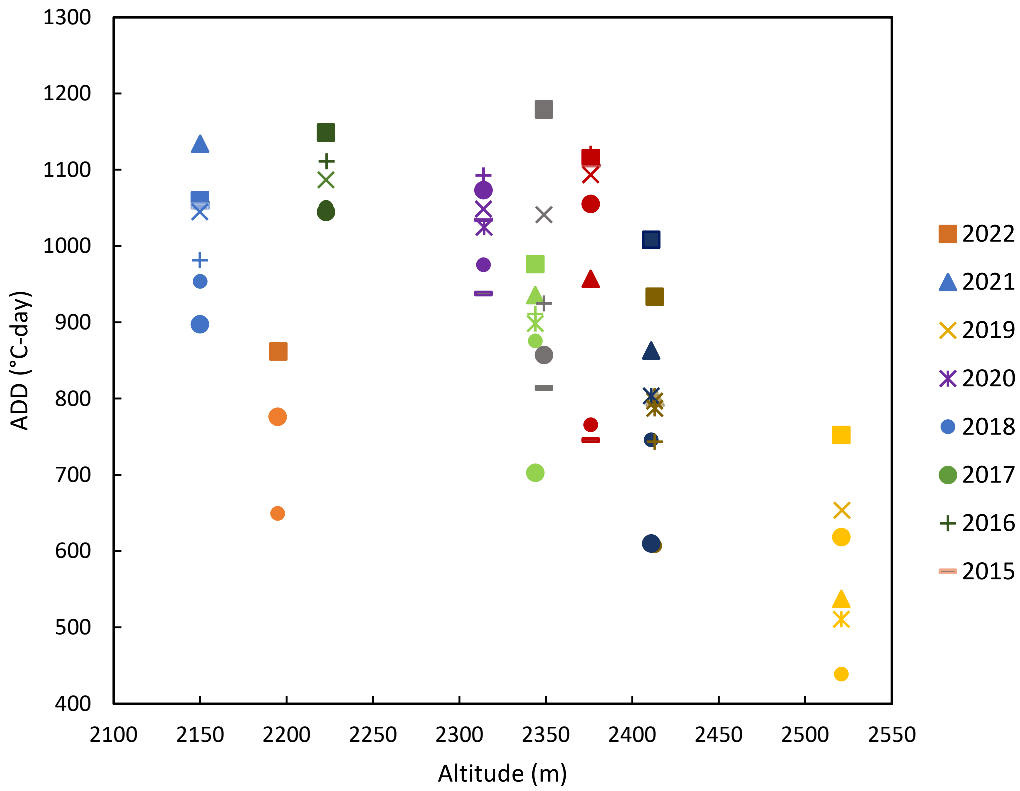


Figure 28. Variability of the range obtained from the ADD matrix for the available data of each lake in the reference period (2015-2022). The different symbols represent the different years analyzed for each identified lake whose annual values are identified through the same color.

4.4.1 INTRA-lake variability (INTER-annual)

The accumulation of degree-days within the same lake is not a constant value: it is subject to climatic conditions and, as seen, to the temperatures reached in that precise period. As for the variability of the ADD parameter within the same lake, it is possible to observe from the graph in Figure 29 how it has apparently grown from year to year even if in non-constant progression. Almost all lakes show the maximum value of ADD as that relating to 2022, of which, among other things, the data series is not complete.

4.4.2 INTER-lake variability

If we evaluate the accumulation of degrees-round between different lakes, it emerges that for lakes at higher altitudes the variability, the amplitude of the range in which the value of ADD varies, is greater than for lakes located at lower altitudes. This, from the climatic point of view, means that the temperature variability is all the wider and more significant as the altitude increases.

Figure 29. Estany Dellui as seen from the Pic de la Pala de Morrano (Pyrenees, Spain).

There is also a clear difference in ADD values between lakes at different altitudes, such as Tres Estany Baix (in purple) and Mig or Superior (in blue and brown) whose difference in altitude is only 100 m. In orange are printed the values relating to Lake Subenuix which has values much lower than the other lakes and close to those of Lake Cap del Port located at 400 m above sea level: this shows us how the influence of the slope, in the case of the Subenuix the north, and therefore the exposure to solar radiation is a predominate factor to determine the ADD value of the system.

The maximum value of ADD is linked to the Estany Dellui which is in the Valle de Dellui very open and exposed to the south: these two factors allow it to reach very high values of ADD and maximum temperatures.

4.4.3 Observed variability

Table 7 summarizes the matrix obtained from the calculation of range as explained above. It is evident that the annual variability is much more significant than that between lakes. That is, the characteristics of a lake in a given year can be taken as a reference for the entire region as certainly between one lake and another the variability of the cumulative °C-day value, as seen, will be linked to minimal local climatic and geographical factors compared to the INTRA-lake variability for different years. Overall, it emerges that the inter-annual variability is less between distinct lakes and greater within the same lake.

Table 7. Summary of the calculation of the range intra and inter lake.

	MAX	MIN	RANGE	MEAN
INTRA-YEAR	483	104	379	267
INTRA-LAKE	1375	439	937	530

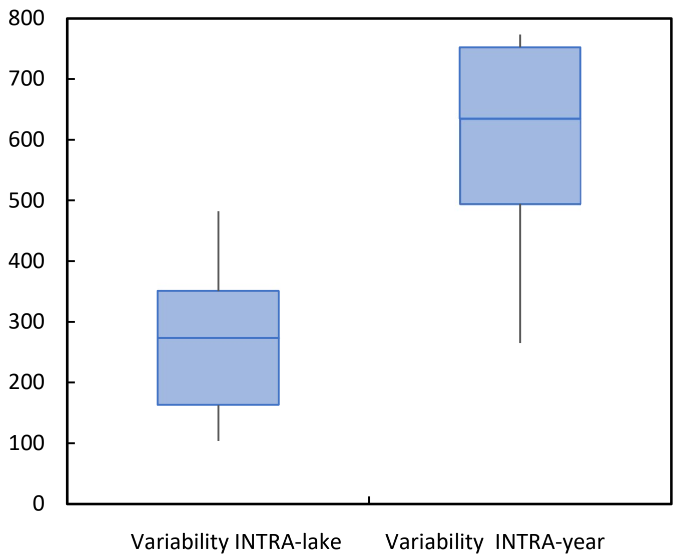


Figure 30. Graph Box Plot that shows the variability INTRA-lake e INTRA-year for the set of data analyzed.

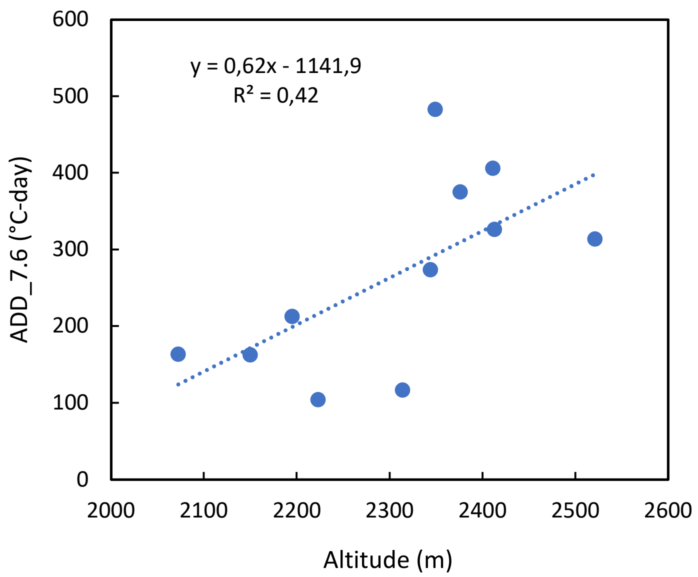


Figure 31. Relationship between the variability of the ADD (range) for the various lakes and their altitude and related equation.

It was also observed that the variability range of ADD, *i.e.* the calculated range, would seem to vary with the altitude and therefore have a linear relation with an R^2 equal to 0.41. The coefficient of determination does not seem to be sufficiently significant, but since it represents the change in the values of the function that can be justified by the variation of the dependent variable, it could be affected by the minimum amount of data analyzed for this purpose (only 11 lakes). Therefore, it is considered appropriate to refer the evidence to a more in-depth study in which the relationships with other topographic variables in comparison are also evaluated.

4.4 Relationships between variables

Below is the correlation matrix created for the main variables analyzed within this study.

Table 8. Correlation matrix between the main variables analyzed.

	IceCoveredDays	IceFreeDays	ADD_7.6_1.5	ADD_4_1.5	MaxTa	MinTa	Days >20°C	's (Melting -Tn	MaxTa1,5(ºC)	Days >4-7.6	Days >7.6	Altitude (m)	Area (Ha)	MeanTa
IceCoveredDays	1,00	-1,00	-0,44	-0,56	0,09	-0,14	0,00	-0,60	-0,04	-0,04	-0,23	0,48	0,23	-0,55
IceFreeDays	-1,00	1,00	0,44	0,56	-0,09	0,14	0,00	0,60	0,04	0,04	0,23	-0,48	-0,23	0,55
ADD_7.6_1.5	-0,44	0,44	1,00	0,90	0,40	0,16	0,58	0,19	0,67	0,13	0,02	-0,65	-0,58	0,81
ADD_4_1.5	-0,56	0,56	0,90	1,00	0,32	0,28	0,44	0,28	0,58	0,14	0,18	-0,63	-0,56	0,86
MaxTa	0,09	-0,09	0,40	0,32	1,00	-0,33	0,56	-0,15	0,49	0,13	-0,02	-0,14	-0,25	0,31
MinTa	-0,14	0,14	0,16	0,28	-0,33	1,00	-0,13	0,12	0,22	0,18	-0,22	-0,08	-0,02	0,46
Days >20°C	0,00	0,00	0,58	0,44	0,56	-0,13	1,00	-0,07	0,67	0,10	-0,09	-0,30	-0,40	0,33
Days (Melting -Tmax)	-0,60	0,60	0,19	0,28	-0,15	0,12	-0,07	1,00	-0,01	0,02	0,29	-0,29	-0,25	0,28
MaxTa_1,5(ºC)	-0,04	0,04	0,67	0,58	0,49	0,22	0,67	-0,01	1,00	0,02	-0,23	-0,35	-0,48	0,52
Days >4-7.6	-0,04	0,04	0,13	0,14	0,13	0,18	0,10	0,05	0,02	1,00	-0,24	0,10	0,26	0,33
Days >7.6	-0,23	0,23	0,02	0,18	-0,02	-0,22	-0,09	0,29	-0,23	-0,24	1,00	-0,13	-0,35	-0,03
Altitude (m)	0,48	-0,48	-0,65	-0,63	-0,14	-0,08	-0,30	-0,29	-0,35	0,10	-0,13	1,00	0,62	-0,56
Area (Ha)	0,23	-0,23	-0,58	-0,56	-0,25	-0,02	-0,40	-0,40	-0,48	0,26	-0,35	0,62	1,00	-0,37
MeanTa	-0,55	0,55	0,81	0,86	0,31	0,46	0,33	0,28	0,52	0,16	-0,03	-0,56	-0,37	1,00

≤ 0,3
0,3 - 07
≥ 0,7

From this it emerges that, obviously, the calculation of the ADD for the two thresholds considered (7.6 and 4 ° C) are closely related values. The ADD value is also well correlated with the maximum temperature variables, the number of days that the lake has maintained a temperature above 20 ° C and the average temperature. The number of days without ice cover (Ice Free Days) is related to the average temperature: therefore, the higher the average temperature, the greater the days when the lake has the ice-free surface. This parameter is also related to the ADD as it has been seen as the only summer period, outside the limnological winter, contributes positively to the calculation of the DD and therefore ADD. Instead, the number of days in which the ice cover appears on the surface of the lake, would seem to be related only to the altitude parameter: it can be explained by the fact that to form the ice sheet, you need to reach 0°C air temperature. Obviously, the moment in which this occurs depends on the atmospheric conditions, but above all on the altitude at which they are analyzed.

4.4.1 ADD relationship and maximum temperature

Based on the available data, the correlation between the maximum annual temperature value and the ADD value has been demonstrated (Sabas et al., 2021). This shows how a higher maximum temperature (extreme heat peaks) are strongly correlated with a higher energy storage and therefore with an anticipation of snow melting, a rapid and sudden change in climatic conditions of the basins.

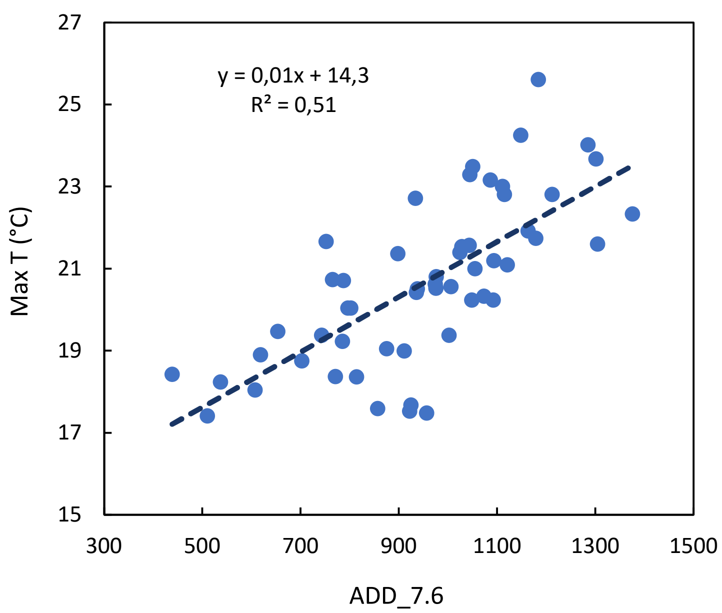


Figure 32. Relationship between the maximum temperature and the ADD: in dark blue it is indicated the trend line (linear regression) obtained.

4.5 Hints at mixing

The mixing of water occurs naturally in these lakes located in the temperate climate zone.

Graphs were obtained through the thermistor chains positioned on a vertical at different depths – between 3 and 4, depending on the depth – of the lake. They show the trend of temperatures at different altitudes and thus characterizing the states of these systems. It emerges that all the lakes examined freeze in the winter season (even if this condition is a function of altitude and lake area): in our case most of the lakes are above the tree line (about 2300 m for the Pyrenees chain), while the size of the lake basin is highly variable (from 0,3 to 7,4 Ha). For this reason, in the following observations an attempt has been made to divide the analysis according to these two characteristics.

The area of the lake is an important variable to which it is possible to correlate the mixing depth, and, by extension, the amount of heat accumulated in the epilimnion as well as the formation of the ice cover.

The lakes considered are mostly dimitic, that is, they stratify in winter and summer, while in autumn and spring they undergo two periods of complete mixing. The mixing of the spring period is always very short and, in all lakes, does not exceed two weeks, while the autumn one also comes to periods of 2 months.

According to (Martin et al. 2010), the systems are more stratified in winter than in summer: at the same time, it can also be said that lakes that are too warm mix less often. Lakes at higher elevations, with normally lower temperatures, are more significantly stratified than lakes at lower altitudes in both winter and summer (see graphs in Figures 33 and 34).

With the same area and altitude, there is the same mixing in terms of period and duration, as well as the importance – in terms of magnitude – of stratification. This shows that the fundamental parameters for this evaluation are the altitude and size of the lake: the parameter relating to wind speed, the main responsible for mechanical mixing and the phenomenon of wind drift, would have been considered significant, but there are not enough data about it.

With the same area, but for different altitudes there are no significant differences in the autumn mixing periods. Conversely, at the same altitude, but for different areas the summer stratification is much less evident. This indicates that in summer smaller lakes are more subject to mixing tending to turn into polymictic lakes.

In terms of the depth of the reservoir, it is possible to observe how, at the same altitude, deeper lakes are more stratified in summer.

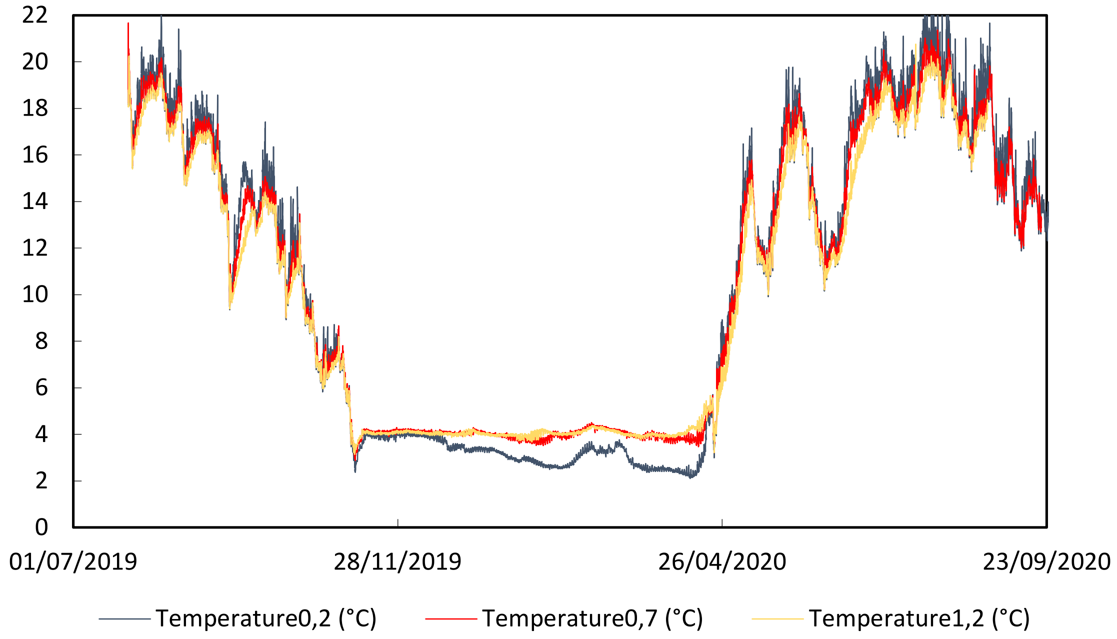


Figure 33. Graph showing the temperature trend over time inside the Estany de Closell (2.074 m).

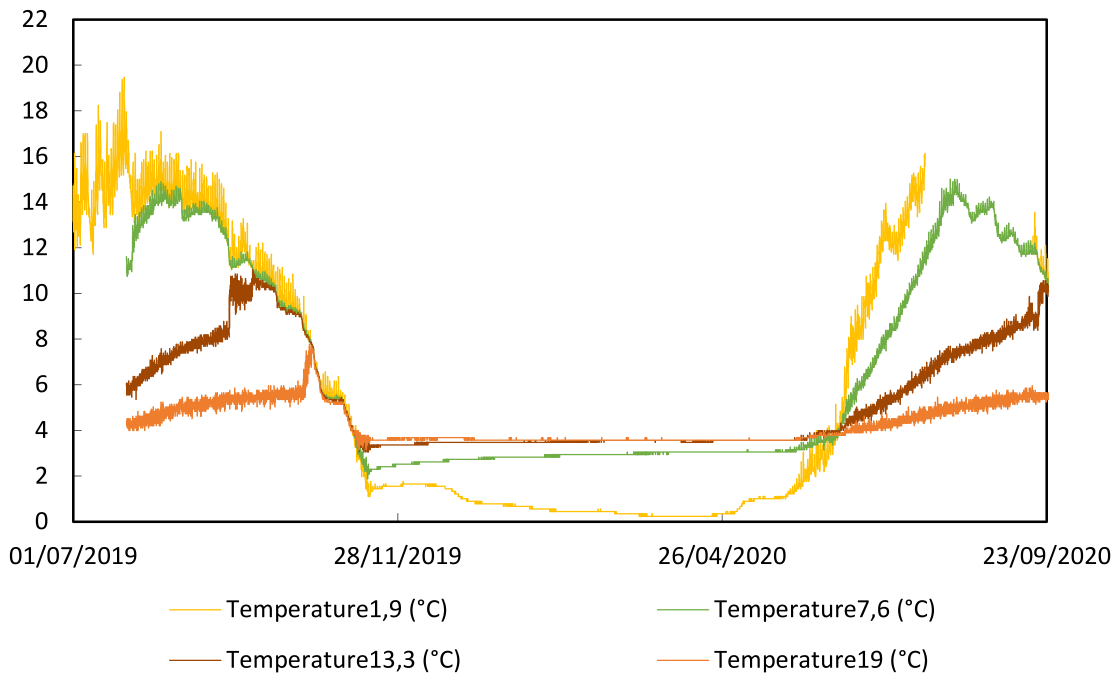


Figure 34. Graph showing the temperature trend over time inside the Estany Cap de Port (2.521 m).

Even the mixing capacity over the years would seem to evolve towards much more stable and less mixing-prone systems. This trend is not directly observable in the available data set, but there is a decrease in mixing days in almost all lakes. The mixing capacity of lakes is subject to change due to climate change (Gaudard et al. 2017). It is expected that with increasing temperatures, summer stratification will last longer, while winter stratification will occur less frequently and consequently decrease duration and ice formation.

For lake ecosystems, as seen, they are particularly subject to climate change and the reduction of mixing capacity, its depth, or its absence, heavily affect it. The frequency and intensity of this phenomenon are two fundamental characteristics for the good ecological status of the water body, as they are responsible for the concentration and balance of oxygen and nutrients along the entire depth of the water.

Chapter 5
Conclusions

The results obtained, presented in the previous chapter, must be considered as preliminary about a study on the variables that most characterize these systems.

The aim of the thesis work presented here was to manipulate the databases relating to temperature measurements and weather conditions to estimate data series as complete and coherent as possible. The manipulations in some cases have been rejected in order not to pollute and compromise the results that have nevertheless appeared, in some cases, uncertain due to the lack of data available.

The mountain range of the central-eastern Pyrenees is a region dotted with small lakes of glacial origin (almost 3000) and is located north of Catalunya (Spain). These lakes undergo freezing of the surface in winter: this has also happened in the reference period as they are still located at an altitude above 2000 m. It has been seen that the two events that determine the duration of the ice cover are the date of ice-on and ice-off: these have shown almost a constant interval for all the lakes and throughout the period analyzed without showing significant imbalances. Most of the lakes analyzed place the ice-on date between the end of October and the first days of November, while the ice-off date from mid-May to the first days of June (for those located at higher altitudes). It emerges from the correlation matrix between, and the main variables analyzed that altitude is the main conditioning effect on the duration of the ice cover (in agreement with Sabas et al., 2021) as the surface temperature of the lake water in summer and early autumn decreases with altitude. Water temperature is closely related to air temperature as a function of altitude.

It has also been seen how meteorological factors – such as precipitation– can greatly affect the temperature of the lake's waters. Some studies would correlate autumn precipitation with the formation of surface ice (Preston et al. 2016): this is because precipitation brings water into the lake by mixing the waters and therefore causing a decrease in temperature, as seen by comparative graphs, and therefore anticipating the formation of ice.

The time period analyzed (2015-2022) showed significant changes especially in terms of increase in the temperature of these bodies of water equal to 2.6 ° C on average and with a growth rate of 4% per year. 2022 turned out to be the hottest year ever recorded, explaining a phenology in the lakes clearly distinct from the other years analyzed. First of all, the value of ADD (Accumulated Degree Days) reached is about 160 ° C-day higher than the maximum of previous years (2016):

in particular, this difference and increase would seem to be almost the same in all basins. The variability (through the calculation of the range) of this inter-annual cumulative parameter for each individual pond and intra-lake was then analyzed, from which it emerged that the variability between one year and another is significantly greater, that is, more significant than the differences expressed in the same year between different lakes – despite these being positioned at different altitudes, totally different geographical points, and exposures of the slopes. Despite this, there was a good linear correlation between the range (variability) between lakes and the altitude at which they are located. However, the report obtained needs to be confirmed by extending the area of analysis to a greater number of elements. Finally, the linear relationship between maximum temperature and ADD values achieved by the systems for each year judged as significant was confirmed. ADD is closely related to summer water temperatures, which are its main contribution, and secondly, to autumn air temperatures. Since air temperatures decrease with altitude, the correlation between ADD and altitude has occurred: in particular, lakes at higher altitudes have lower ADD values reached and at the same time also have longer times of ice surface cover.

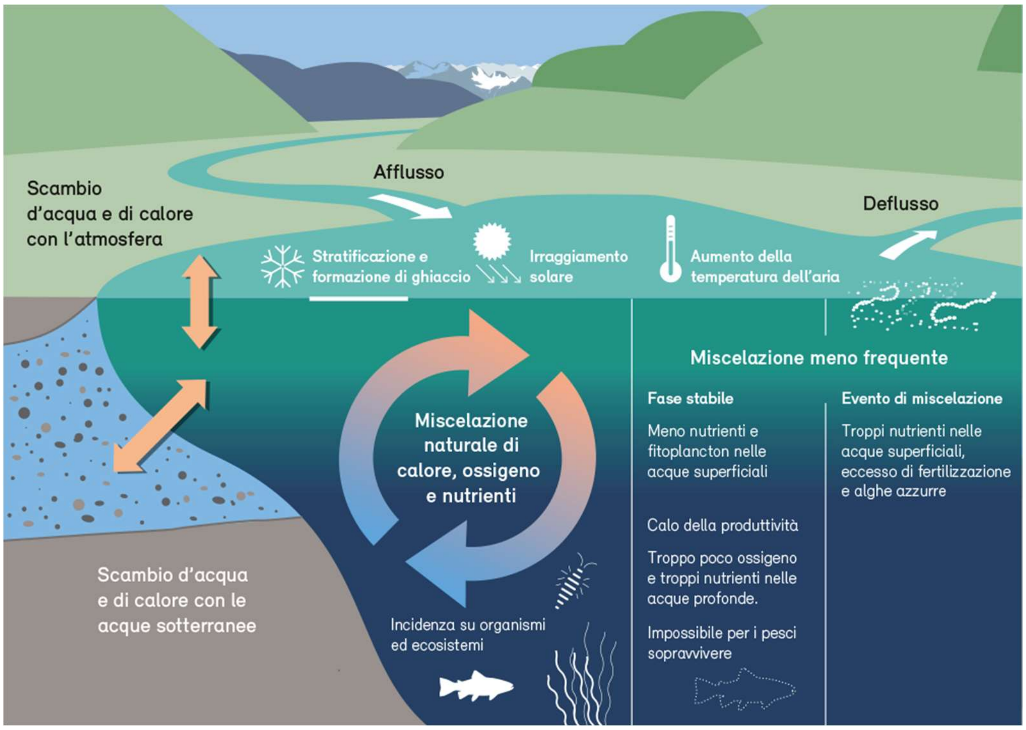


Figure 35. Image that briefly shows the "chain" reactions related to the effect of climatic change on lake ecosystems. Source: Gaudard et al. (2017).

In conclusion, climate change is certainly having impacts on the hydrodynamics of lakes by influencing water temperature and mixing depth, which in turn have effects on dissolved oxygen concentrations and nutrient cycles. Indirect effects include changes in the microclimates of hydrological basins containing lakes, but presenting local effects that are difficult to measure. While the so-called "chain" effects of climate change, which are also based on water temperature, are much more evident. An increase in temperature of these water basins, as also verified here, leads to chemical-physical imbalances and variations in the chemical composition of the waters which in turn are reflected on the life of flora and fauna present in these ecosystems. Particularly relevant are the changes in the mixing capacity of lake ecosystems: this is considered a starting point for a subsequent analysis. These variations are observable from year to year when the reconnaissance and data collection from the installed thermistors is carried out.

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Centro Euro-Mediterraneo sui cambiamenti climatici: www.cmcc.it

La convenzione delle Alpi: www.alpconv.org

Annex I

Technical characteristics of the thermistors used for the collection of the analyzed data:

Measurement Range
Temperature: -20° to 70°C (-4° to 158°F)
Light: 0 to 320,000 lux (0 to 30,000 lumens/ft^2)

Accuracy
Temperature: ± 0.1°C from 0° to 50°C (± 0.95°F from 32° to 122°F), see Plot A in manual

Resolution
Temperature: 0.14°C at 25°C (0.25°F at 77°F), see Plot A in manual
Drift: Less than 0.1°C/year (0.2°F/year)

Memory
UA-002-08: 8K bytes (approximately 3.5K combined temperature and light readings or events)
UA-002-64: 64K bytes (approximately 28K combined temperature and light readings or events)

Light intensity: Designed for measurement of relative light levels, see Plot D in manual for light wavelength response

Response Time
Airflow of 2 m/s (4.4 mph): 10 minutes, typical to 90%
Water: 5 minutes, typical to 90%
Time accuracy: ± 1 minute per month at 25°C (77°F), see Plot B in manual

Materials: Polypropylene case; stainless steel screws; Buna-N o-ring
Weight: 18 g (0.6 oz)
Dimensions: 58 x 33 x 23 mm (2.3 x 1.3 x 0.9 inches)
Environmental Rating: IP68

The CE Marking identifies this product as complying with the relevant directives in the European Union (EU).

Operating Range
In water/ice: -20° to 50°C (-4° to 122°F)
In air: -20° to 70°C (-4° to 158°F)
Water depth rating: 30 m from -20° to 20°C (100 ft from -4° to 68°F), see Plot C in manual

NIST traceable certification: Available for temperature only at additional charge; temperature range -20° to 70°C (-4° to 158°F)

Battery life: 1 year typical use
Battery Type: CR2032

Brand	Onset HOBO
Channel(s)	2
Onset Product Series	Pendant (UA)
Typical applications	Environmental (Outdoor), Field Research, Water Quality
Measurements	Light Intensity, Temperature, Water Temperature

Annex II

The ADD graphs (°C-day) obtained for each of the 11 lakes analyzed are presented in sequence together with a map of their location on the territory to allow a better interpretation of the results also according to their position. The dashed line in black shows the data availability limit for the year 2022, the characterization objective of the analysis. Reconstructed data were also reported were significant.

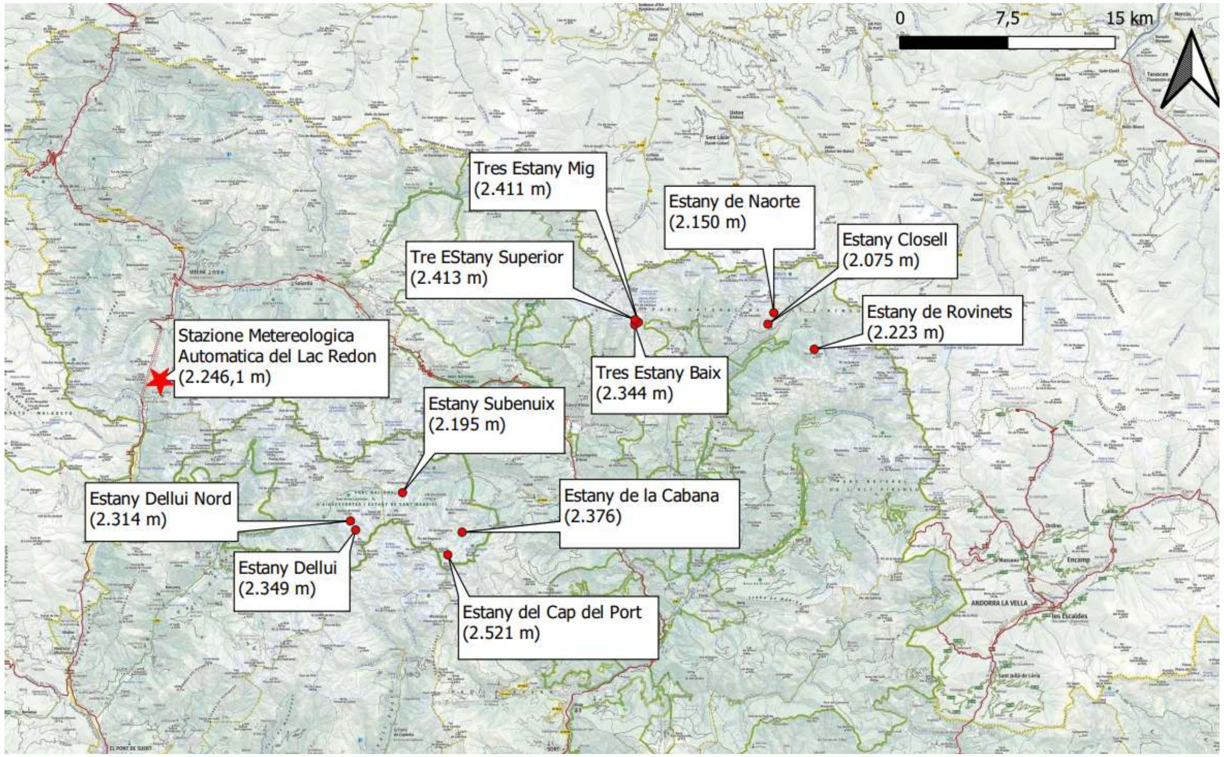
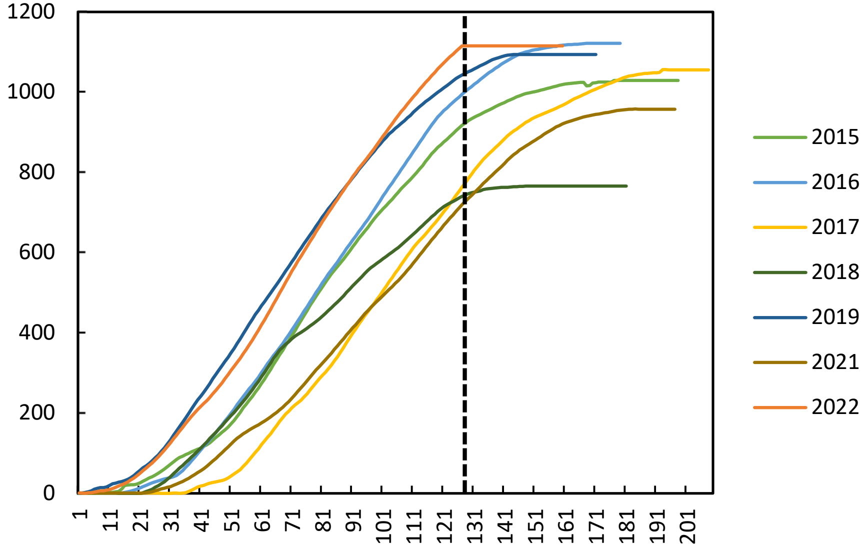
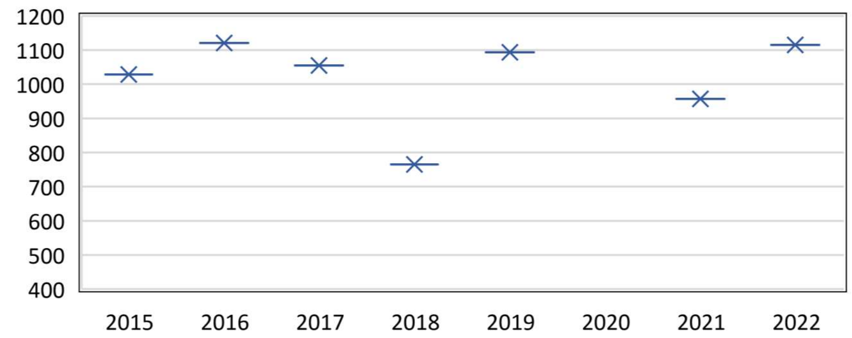


Figure 36. Map of the distribution of the analyzed lakes with the relative altitudes.

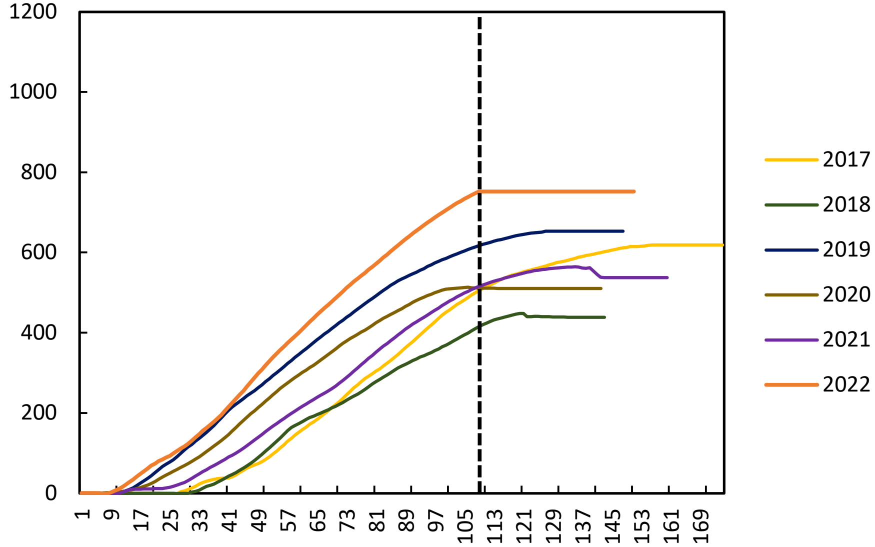
CABANA ADD 7.6



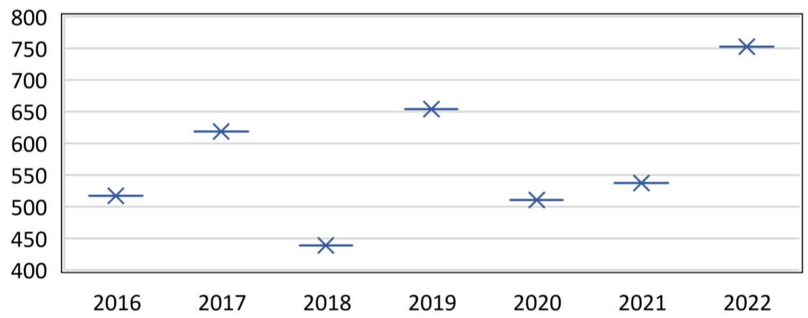
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD_7.6_1.5
2015	02/11/2014	08/05/2015	187	178	1028,39
2016	21/11/2015	15/05/2016	176	189	1120,84
2017	21/11/2016	14/04/2017	144	221	1055,16
2018	10/11/2017	28/05/2018	199	166	765,04
2019	01/11/2018	28/05/2019	208	157	1093,29
2021	20/11/2020	28/04/2021	159	206	956,86
2022	08/11/2021	16/05/2022	189	176	1115,13



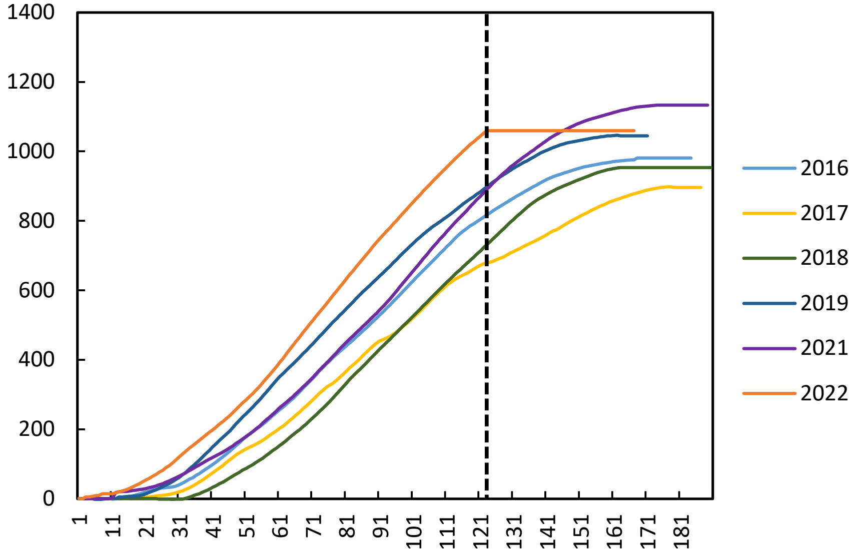
CAP DEL PORT ADD 7.6



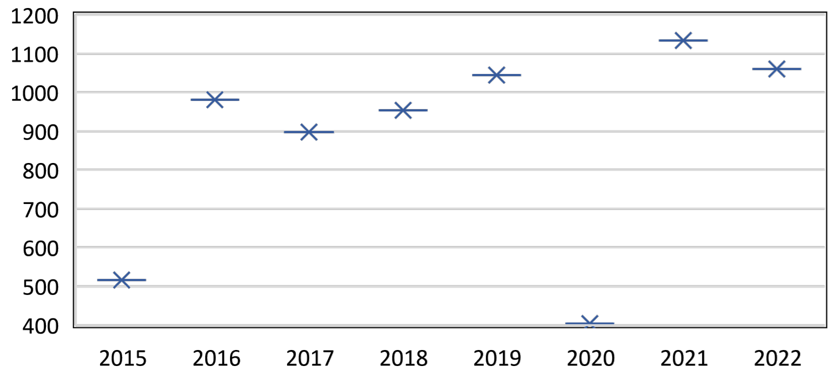
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD_7.6_1.5
2016	23/11/2015	01/06/2016	191	174	517,06
2017	21/11/2016	23/05/2017	183	182	618,34
2018	19/11/2017	11/06/2018	204	161	438,58
2019	02/11/2018	15/06/2019	225	140	653,68
2020	07/11/2019	18/06/2020	224	141	510,53
2021	08/11/2020	03/06/2021	207	158	537,17
2022	10/11/2021	03/06/2022	205	160	752,16



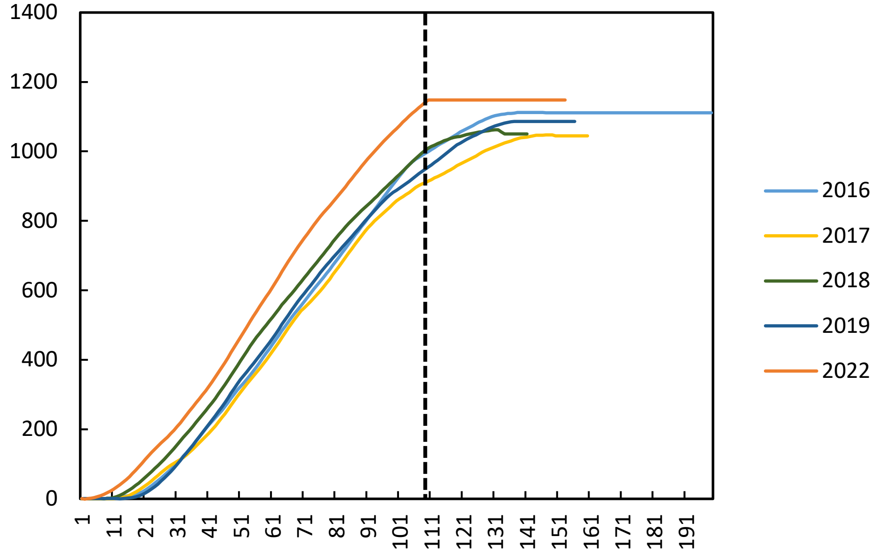
NAORTE ADD 7.6



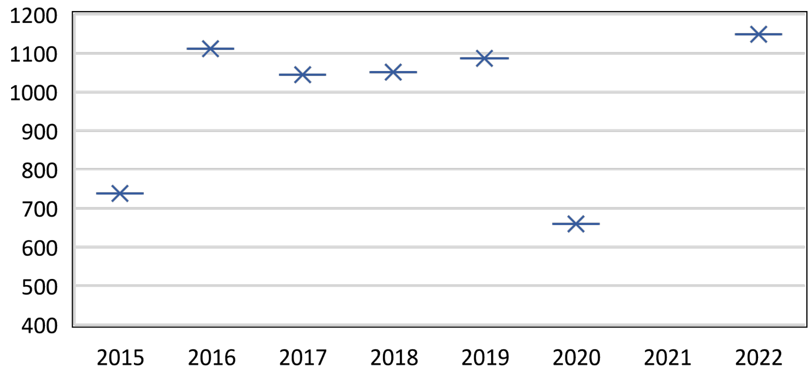
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2016	25/11/2015	23/05/2016	180	185	981,20
2017	28/11/2016	11/05/2017	164	201	897,31
2018	15/11/2017	18/05/2018	184	181	953,68
2019	27/11/2018	27/05/2019	181	184	1044,44
2022	02/10/2021	18/05/2022	228	137	1059,94



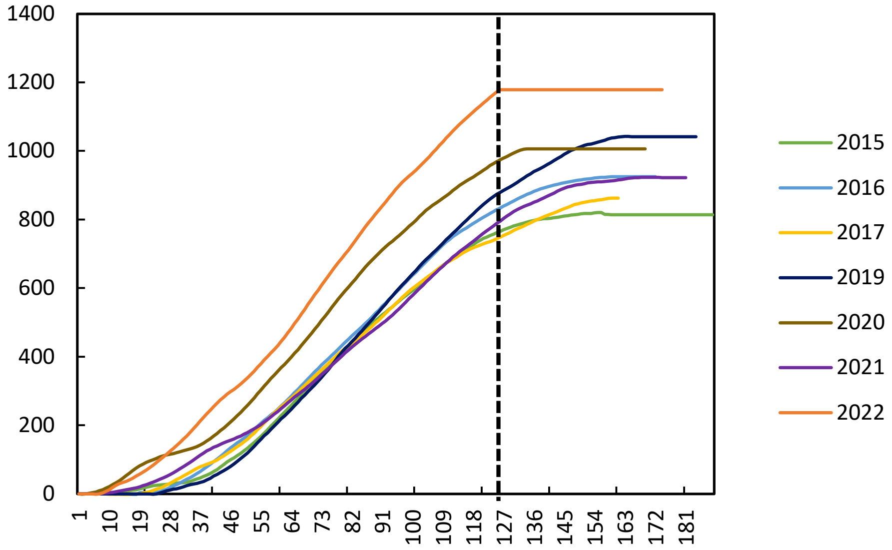
ROVINETS ADD 7.6



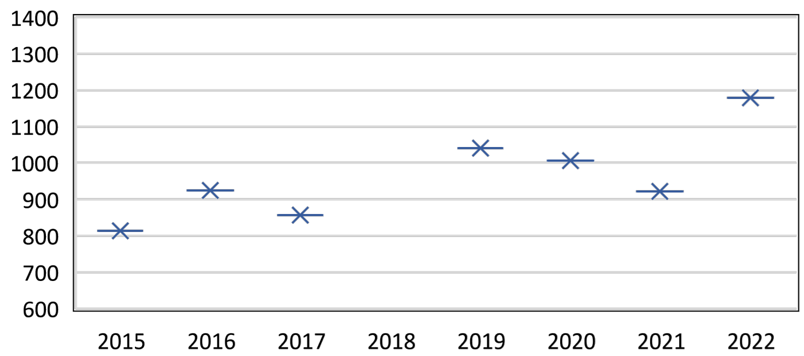
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2016	14/11/2015	02/06/2016	201	164	1111,22
2017	04/11/2016	01/06/2017	209	156	1044,55
2018	06/11/2017	13/06/2018	219	146	1050,64
2019	29/10/2018	04/06/2019	218	147	1086,61
2022	05/11/2021	01/06/2022	208	157	1148,52



DELLUI MIG ADD 7.6



YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1.5
2015	28/11/2014	12/05/2015	165	200	937,70
2016	23/11/2015	09/05/2016	168	197	1092,27
2017	12/11/2016	04/05/2017	173	192	1073,14
2018	10/11/2017	25/05/2018	196	169	975,42
2019	30/10/2018	13/05/2019	195	170	1048,38
2020	06/11/2019	06/05/2020	182	183	1024,68
2022	10/11/2021	15/05/2022	186	179	1043,13



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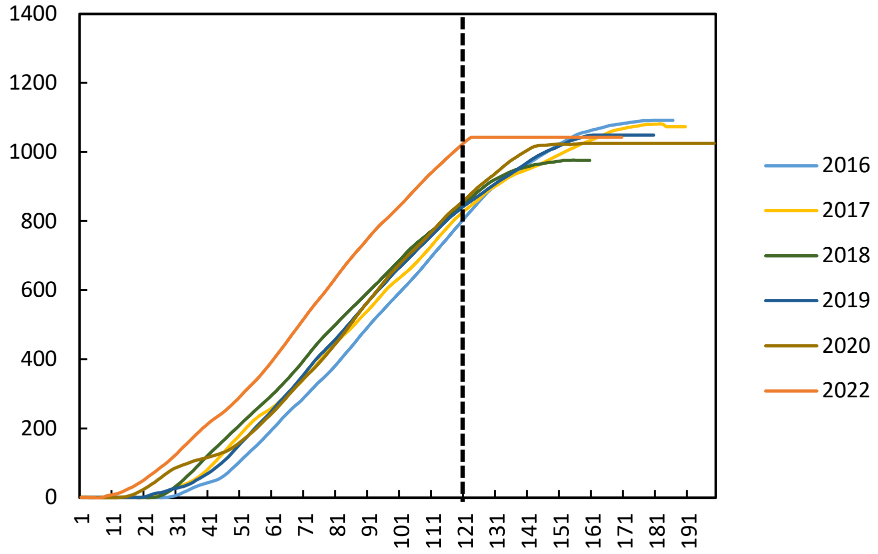
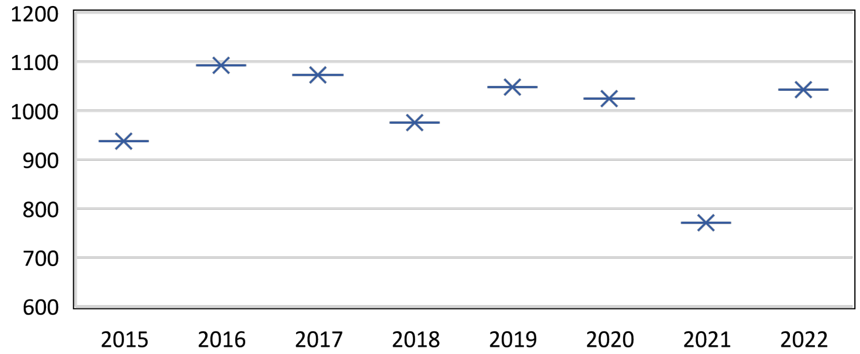
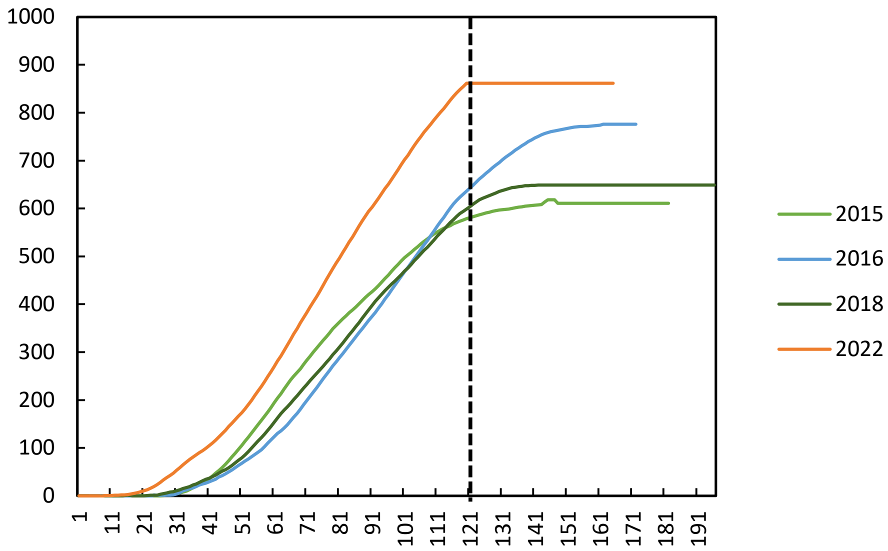


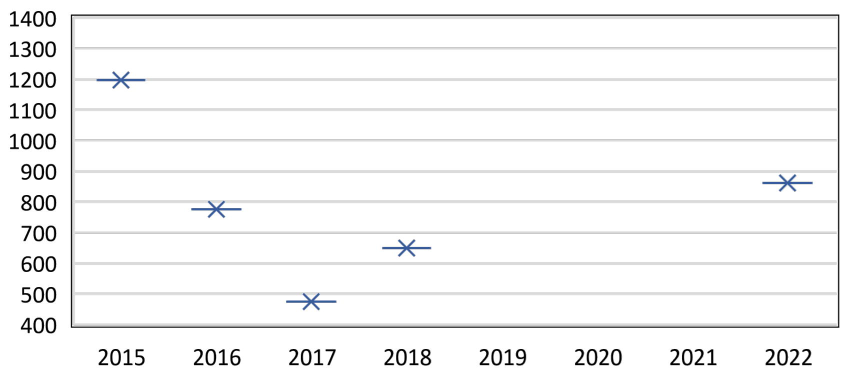
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2016	20/11/2015	07/06/2016	200	165	910,83
2018	09/11/2017	16/06/2018	219	146	875,46
2019	31/10/2018	13/06/2019	225	140	973,92
2020	08/11/2019	18/05/2020	192	173	898,21
2021	20/11/2020	29/05/2021	190	175	935,66
2022	09/11/2021	27/05/2022	199	166	976,13



SUBENUIX ADD 7.6



YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2015	11/11/2014	26/05/2015	196	169	1196,84
2016	22/11/2015	22/05/2016	182	183	775,97
2018	14/11/2017	06/06/2018	204	161	649,15
2022	10/11/2021	20/05/2022	191	174	861,69



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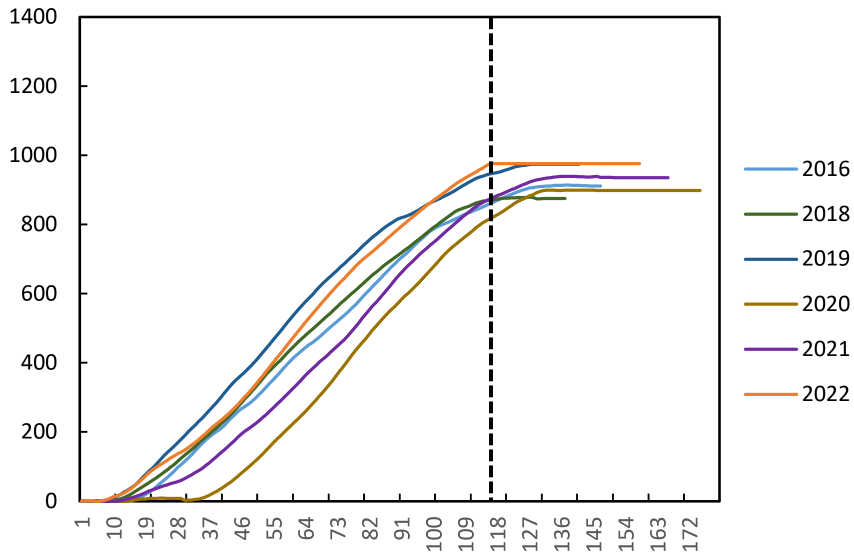
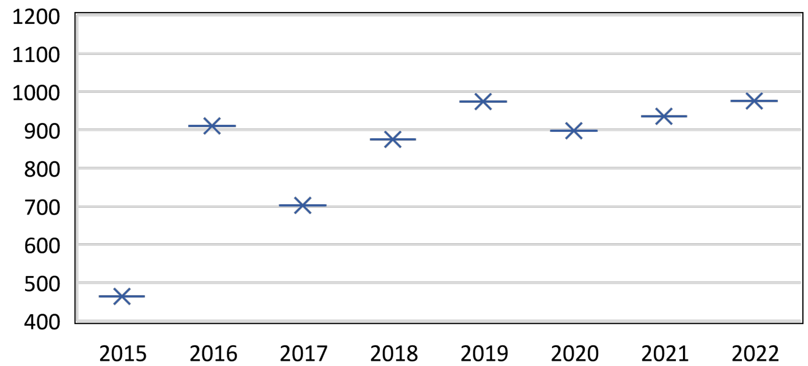
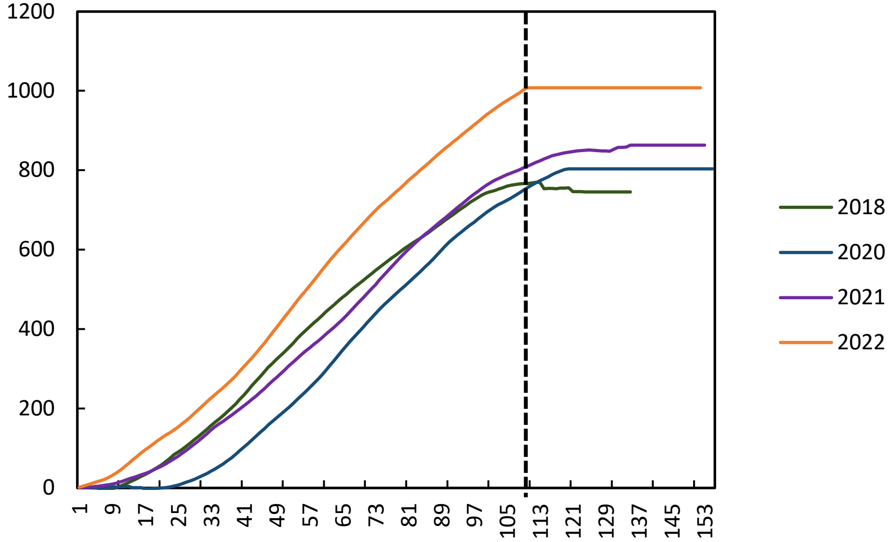


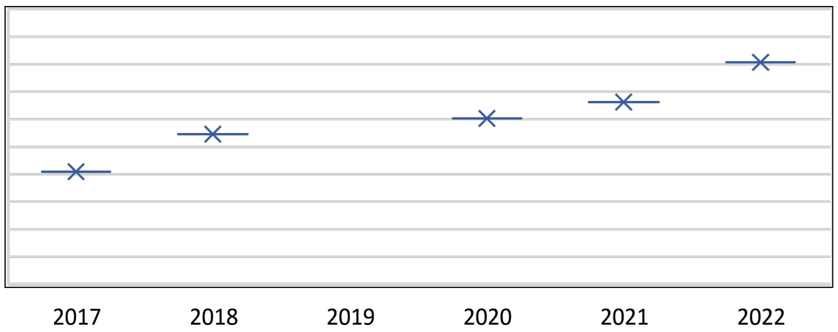
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2016	20/11/2015	07/06/2016	200	165	910,83
2018	09/11/2017	16/06/2018	219	146	875,46
2019	31/10/2018	13/06/2019	225	140	973,92
2020	08/11/2019	18/05/2020	192	173	898,21
2021	20/11/2020	29/05/2021	190	175	935,66
2022	09/11/2021	27/05/2022	199	166	976,13



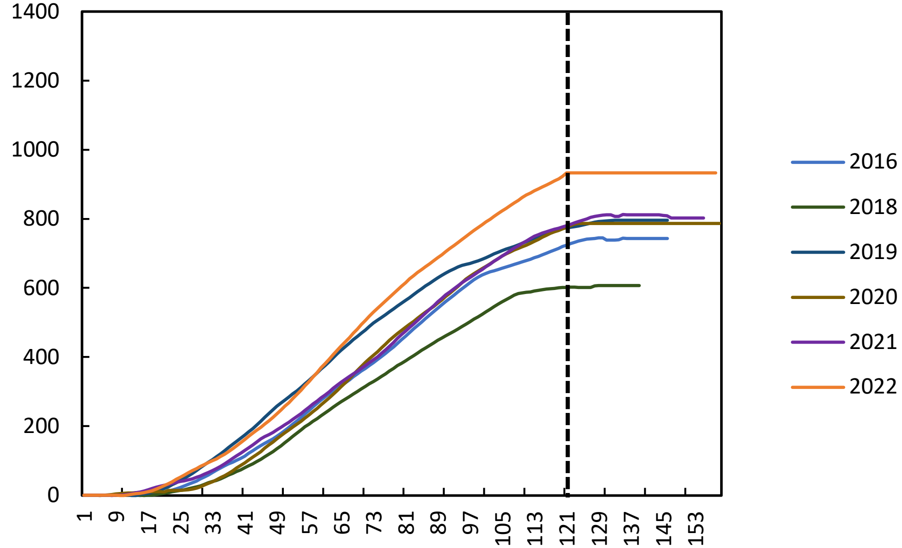
TRES ESTANY MIG ADD 7.6



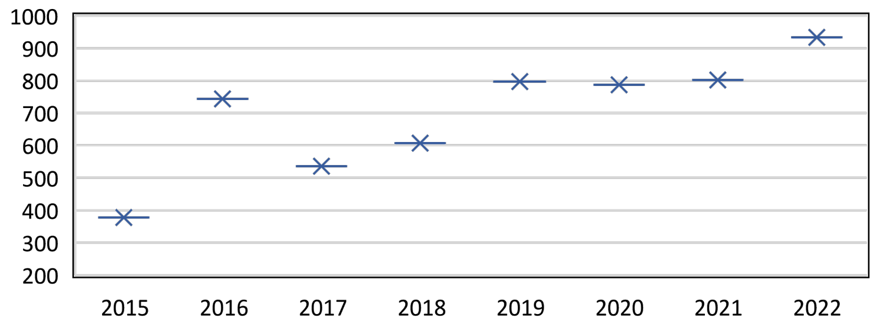
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2018	05/11/2017	19/06/2018	226	139	745,67
2020	13/11/2019	24/05/2020	193	172	803,39
2021	16/10/2020	30/05/2021	226	139	862,88
2022	09/11/2021	29/05/2022	201	164	1007,95



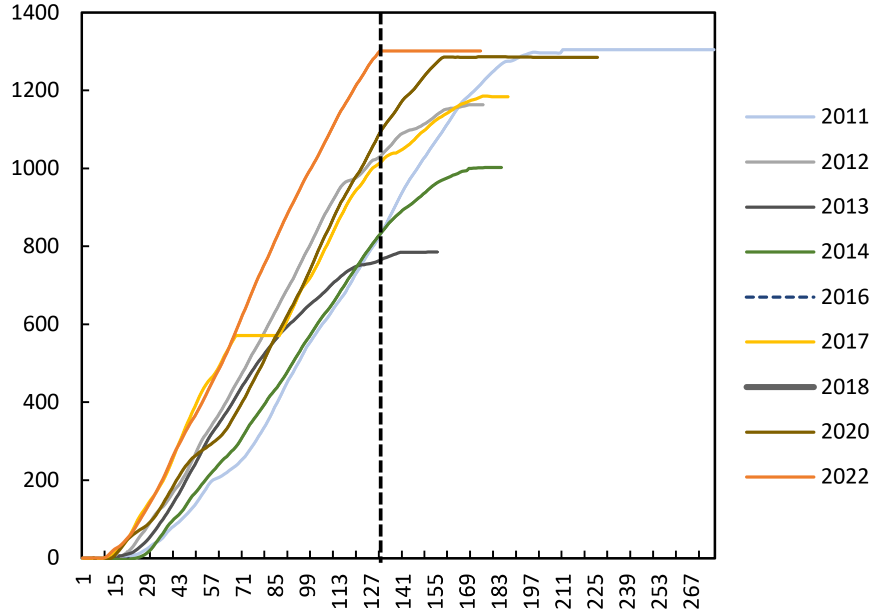
TRES ESTANY SUPERIOR ADD 7.6



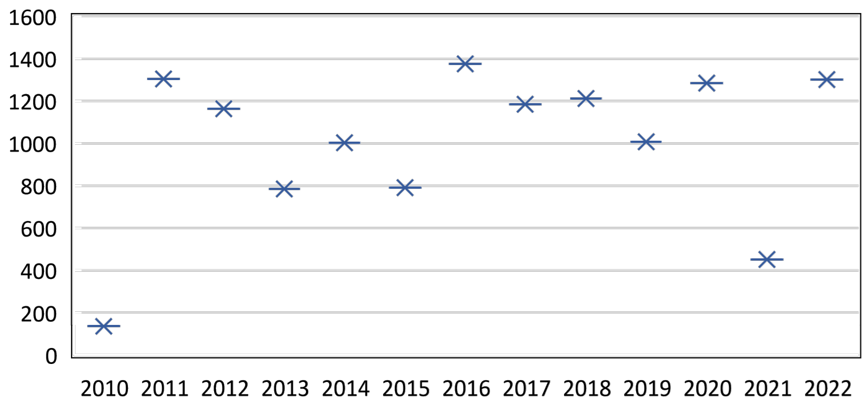
YEAR	FREEZING	MELTING	ICE_C_DAYS	ICE_F_DAYS	ADD (>7.6) 1,5
2016	21/11/2015	08/06/2016	200	165	743,13
2018	07/11/2017	14/06/2018	219	146	607,15
2019	01/11/2018	08/06/2019	219	146	796,57
2020	09/11/2019	26/05/2020	199	166	787,08
2021	22/11/2020	30/05/2021	189	176	802,14
2022	10/11/2021	27/05/2022	198	167	933,53



CLOSELL ADD 7.6



YEAR	FREEZING	MELTING	ICE_C_DAY	ICE_F_DAY	ADD_7.6_1.5
2011	16/11/2010	05/04/2011	140	225	1304,74
2012	30/11/2011	09/05/2012	161	204	1163,36
2013	27/11/2012	12/06/2013	197	168	785,22
2014	11/11/2013	08/05/2014	178	187	1002,27
2016	22/11/2015	10/05/2016	170	195	1375,46
2017	09/11/2016	05/05/2017	177	188	1183,89
2018	07/11/2017	09/05/2018	183	182	1212,22
2019	24/11/2018	09/05/2019	166	199	1007,30
2020	07/11/2019	20/04/2020	165	200	1284,94
2022	07/11/2021	10/05/2022	184	181	1301,52



Annex III

The matrix used for the calculation of the rank and the determination of the variability of the inter-lake and the inter-annual dataset is reported in the Table.

		Lake name											Variability INTRA-year		
	ADD	Closell	Naorte	Subenuix	Rovinets	Dellui_nord	TEB	Dellui	Cabana	TEM	TES	Cap_del_Port	*max*	*min*	*rank*
Year	2011	1304,74											1163	1305	141
	2012	1163,36											785	1163	378
	2013	785,22											785	785	0
	2014	1002,27											746	1002	257
	2015							813,75	745,56				743	814	71
	2016	1375,46	981,20	775,97	1111,22	1092,27	910,83	924,73	1120,84		743,13		618	1375	757
	2017		897,31		1044,55	1073,14	702,50	696,17	1055,16			618,34	439	1073	635
	2018	1212,22	953,68	649,15	1050,64	975,42	875,46		765,64	709,94	607,15	438,58	439	1212	774
	2019		1044,44		1086,61	1048,38			1093,29		796,57	653,68	654	1093	440
	2020	1284,94				1024,68		988,06			787,08		537	1285	748
	2021										802,14	537,17	537	802	265
	2022	1301,52	1059,94	861,69	1148,52	1043,13	976,13	1178,96	1115,13	1115,99	933,53	752,16	752	1302	549
Altitude (m)		**2072,31**	**2150,00**	**2195,00**	**2223,00**	**2314,00**	**2344,00**	**2349,00**	**2376,00**	**2411,00**	**2413,00**	**2521,00**			
Years considered		4	5	3	5	6	4	5	6	2	6	5			
Variability INTRA-lake	*max*	1212	897	649	1045	975	703	696	746	710	607	439			
	min	1375	1060	862	1149	1092	976	1179	1121	1116	934	752			
	rank	163	163	213	104	117	274	483	375	406	326	314			

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Redigendo questo lavoro di tesi sono giunta alla fine del mio percorso di studi (a volte sofferto) presso il Politecnico di Torino.

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Estany de Saint Maurici, Lleida, Spagna