Climate change and extreme weather: droughts and their impact on Argentinian agriculture

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Climate change has exacerbated extreme events, including dry pulses. The United States, Brazil and Argentina are among the countries that have lately suffered their impact, severely affecting the agricultural production. But, what is meant by drought? Can it be predicted? What consequences does climate change have in that regard, and what will its impact be on Argentina?

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Introduction

Climate change and the extreme weather associated to it have caused a higher volatility in crop production and in the prices of cereals and oilseeds, and it will continue to do so in the coming years. Evidence is overwhelming, and its increasingly necessary to have available algorithms that address the detection and forecast of extreme weather, issue that is addressed by the Rosario Board of Trade through the Rosario Board of Trade (GEA, for its Spanish Acronym). Short-term forecasts (one week to a fortnight) are the ones employed by users in the agricultural field, but are not the most adequate to deal precisely with the origin of production and market volatility.

The alarming effects of the Climate Change and extreme weather require the present approach on "droughts and the agricultural sector", which will be centred on four aspects:

- Generalities and basic concepts
- Drought-measuring tools Indicators and Indices
- Predictability of droughts
- Effects of climate change
- Impacts on Argentina

The subject of climate change and its implications is already installed in all levels of decision-making, from governments to local communities, despite the pressure of certain “sceptics” that deny or belittle the reports by the scientific community in order to defend certain economic interests and divert the attention from the main problem. There are people who, without looking for factual information (physical and biological) on climate change, simply do not believe in it. The recent upsurge of heatwaves, fires, and droughts has raised public opinion awareness on these subjects. We are experiencing it in Rosario, with the historically low water level of the Paraná river.

In a warming world, we unfortunately forecast that the risk for some types of extreme meteorological events increases. For example, with the rise of temperatures in most parts of the world, we expect more heatwaves. At the same time, warmer air can hold more water and, therefore, we forecast more extreme rains.

Individual meteorological events are ultimately unique and are always caused by a combination of different factors, including the local variability of the weather, conditions of the earth’s surface and its interactions with the atmosphere, large-scale patterns of the oceanic temperatures and changes in external drivers (for example, greenhouse gasses, aerosols). Therefore, it cannot be said that an extreme meteorological event was “caused” by global warming or the associated climate change. However, we can estimate if an extreme event has changed due to human-induced climate change, and if so, to which extent, and its probability or intensity.

The increasing impact of human activities not only affects the weather, but also the global environment, so we now refer to it as **global environmental change** (GEC), which addresses the large-scale chemical, biological, geological and physical disturbances of the earth’s surface, the ocean’s surface, and the hydrological cycle, especially focusing on timescales of decades to centuries, human-caused disturbances and their impact on society.

Human action denotes a recent behaviour characterized by the cross-cutting and disproportionate alteration of all of the Earth’s ecosystems, especially by the use of energy from extraction and utilization of fossil fuels. The situation is related to the increase of techno-industrial productivity, as well as the overwhelming growth of the population, together with the hyper-urbanization, soil changes and vegetable coverage. All these impact on the climate, producing changes that are reinforced and intensified by various anthropogenic processes.

As for future climate trends, estimations by the United Nations Intergovernmental Panel on Climate Change (IPCC) based on numerical simulations show, in spite of uncertainties, that even in the most optimistic scenarios the warming will continue (and its consequences) unless emissions are strongly reduced. During the United Nations’ meeting on climate change COP-21, held in Paris in 2015, the world agreed that by the end of the century, the rise of the global temperature should not exceed 2°C over pre-industrial levels. The goal was to limit the rise to 1.5°C, if possible, but there was no progress. According to this agreement, countries promised to meet again every five years and to rise their carbon reduction goals. Due to the pandemics, Glasgow COP-26, planned for 2020, was postponed for November this year.

According to current estimations, it is forecast that the world will exceed the 1.5°C limit in 12 years or less, and that it will reach 3°C of warming by the end of the century, and the meeting in Glasgow could be one were carbon emissions cuts are increased. The situation is urgent (UN Secretary-General recently warned that we are waging a suicidal war against nature) and there already are several countries that have unilaterally committed to assume a zero-emissions legal engagement (the United Kingdom in 2019, the European Union in 2020, and recently China, one of the main emitters).

COVID-19 pandemics showed that the world is not invulnerable and that it can be affected in uncontrollable ways. It provoked an economic shock that made governments react with stimulus packages for reactivating their economies. We expect that, once the pandemics is overcome through universal vaccination programs, the attention turns to another global concern: climate change and the actions to limit its consequences (for example, the reduction of emissions, limitation of consumption, use of renewable energies, waste treatment, etc.).

The "business-as-usual" approach could take us to an unsustainable global situation.

Droughts: generalities and basic concepts

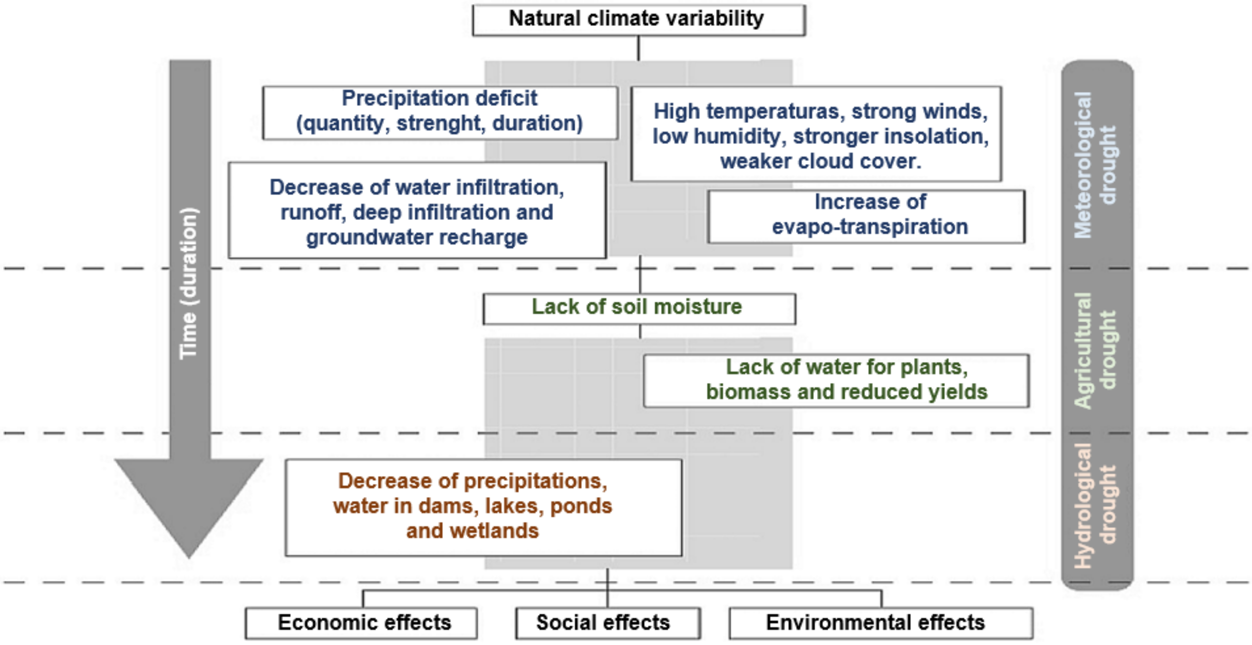
Droughts have been the object of great concern in the main grasslands of the world due to its influence on the production of food, as well as in the degradation of soils due to wind erosion. They were the most important cause of people affected by natural disasters all over the world along the 20th century and, according to the United Nations Office for Disaster Risk Reduction (UNISDR 2015), 50.5 million people all over the world were affected by drought in 2015 only. In recent periods, droughts have severely affected vast areas of the US and Brazil, for example.

Droughts have been directly linked to poverty; according the United Nations Food and Agriculture Organization, they were the cause of one third of the global losses of agricultural production during 2005-2015 for 96,000 million dollars; they have been linked to important negative effects on human health, the increase of gender inequality, the decrease of hydro security, the reduction of the global hydroelectric potential due to changing climate; and they have also been connected to the emergence of armed conflicts and the break of states of peace or, at least, as a concurrent factor to the existence of certain conflicts or political instability (Ref. 1).

In a general sense, **drought** is defined by the Spanish Royal Academy (RAE, for its Spanish acronym) as *"Prolonged period of dry weather. During the drought period, the water available in a geographical region is below the usual parameters, which is why it is insufficient to satisfy the needs of humans, plants an animals."* In the meteorological field, it is usually defined as *deficit of rains during a prolonged period of time –a season, a year, or several years– in relation to the multi-annual statistic median of the region in question, which causes a serious hydrological imbalance*. The lack of rain results in an insufficient water supply for plants, animals and human beings. We should note that there are over 150 definitions of drought in scientific literature (Ref. 2).

It is common to distinguish between different types of drought; *meteorological, hydrological, agricultural/agronomic or hydro-edaphic, socioeconomic,* that define the start, severity, and end of a drought, and refer to the sector, system or social group affected by the phenomenon.

Meteorological drought: When there is a continuously low precipitation. It is the drought from which the remaining types stem, and it usually affects vast areas. The origin of low precipitation is related to the global behaviour of the atmosphere-ocean system, influenced both by natural as by anthropic factors. The atmospheric conditions that cause low precipitation are very variable from one region to another, which is why this drought is connected to a specific region. Although the primary indicator of water availability is precipitation, in many cases this type of drought can also imply higher temperatures, intense winds, low relative humidity, increase of evapotranspiration, reduced cloud coverage and higher sun exposure.



Hydrological drought: It is associated to the effects provoked by low precipitation on the levels of rivers, water reservoirs and aquifers (underground water reservoirs). This drought might not be only due to low rainfall, but also by how the water is used, that is to say, to inadequate human activity.

Agricultural/agronomic or hydro-edaphic drought: It is usually defined as a humidity deficit in the root area to satisfy the needs of a given crop, in a specific place and time. Agronomic drought can be different according to he crop under consideration (wheat, sunflower, corn, soybean, etc.). It can also be distinguished between rain fed agriculture and irrigated agriculture. For rain fed agriculture, it is the soil humidity deficit after a meteorological drought, and it causes negative effects on the crop production and/or the growth of natural vegetation. For irrigated agriculture, it is the scarcity of water to supply irrigation systems due to drought on surface water or groundwater used for agriculture.

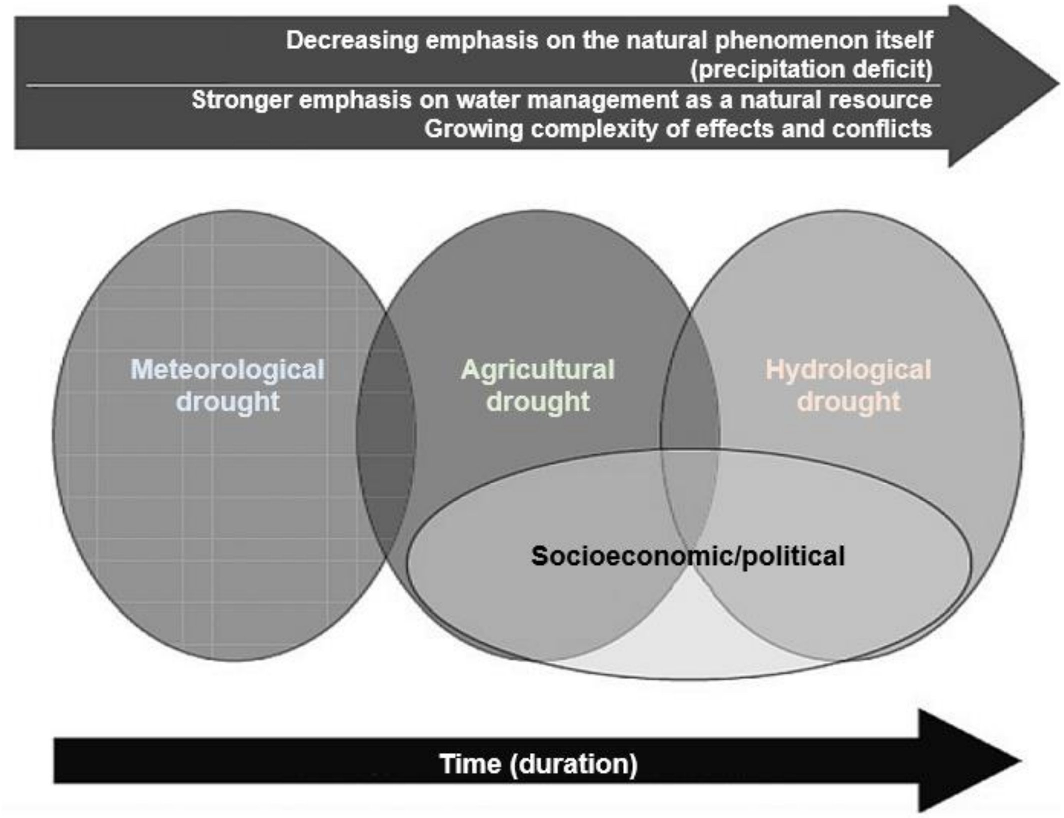
Socioeconomic drought: Shortage of water that affects people and economical activity as a consequence of drought. In order to speak about socioeconomic drought, a water supply restriction is not required, but only that some economic sector is affected by water scarcity with unfavourable economic consequences. The growing pressure of human activity on water resource makes the incidence of socioeconomic drought increasingly higher, with rising economic losses. It can be mitigated with good management.

In recent times, "*flash droughts*" have also been proposed, which correspond to a drought with very fast start or intensification, originated for precipitation rates lower than normal, accompanied by unusually high temperatures, winds or radiation. This definition can be applied to all the previous types.

"*Ecological drought*" has also been coined, and it is defined as an episode of water availability deficit that causes ecosystems to exceed its vulnerability thresholds, affecting the services of the ecosystem and triggering feedbacks with the natural and human systems.

All droughts are, essentially, consequence of a deficit of precipitation (meteorological drought), which in turn can provoke other types of drought, such as the ones defined above.

The following graphics (Source: Drought Mitigation Center, University of Nebraska-Lincoln, United States) illustrate the sequence of drought events and their effects on the types of drought usually accepted, and the interrelations among meteorological, agricultural, hydrological and socioeconomic droughts.



Also, a distinction is usually made between *drought, aridity* and/or *scarcity*.

Drought, understood as a temporary precipitation or natural stream flow anomaly, can produce, or not, a situation of insufficiency of the water supplies, depending on the existing level of water demand in the area and on the general characteristics of the exploitation systems of the resource.

Scarcity represents a permanent situation of deficit in relation to the water demand in a regional resource system, characterized by an arid climate or by a rapid growth of the consumption demands.

Aridity is a natural structural situation of a region and, therefore, also permanent, that must be differentiated from drought, which is a transitory, yet prolonged, natural anomaly.

Drought-measuring tools Indicators and Indices

It is important to distinguish between drought ***indicators*** and ***indices*** since they are often confused.

According to the World Meteorological Organization (Ref. 3), **indicators** are variables or parameters used to describe the conditions of the droughts. We can mention, for example, precipitation, temperature, river flows, levels of groundwater and water reservoirs, soil moisture and snow cover. **Indices**, however, are usually computerized numeric representations of the seriousness of the drought, determined through climate or hydro meteorological data, among which the mentioned indicators are included. They are meant to analyse the qualitative state of droughts during a specific stretch of time.

From the technical point of view, indices are also indicators. Watching the climate in several time scales allows us to recognize short humid periods within long-lasting droughts or short dry periods.

Ref. 3 presents and details a variety of indicators and indices, highlighting how important it is that indicators or indices reflect and represent in a precise way the effects produced during droughts. These effects of droughts may vary as they develop, according to the region and the season.

In this article we will only discuss the most commonly used ones. The interested reader may look up the quoted reference in order to get more information.

As typical indicators, we can mention:

- **DECILES**: Through the complete period of precipitation data collection of a specific place, we can classify the frequency and distribution of precipitation. The first decile is made up by the amount of rainfall where the lowest 10% of the values is not exceeded, and the fifth decile constitutes de median. In this methodology, daily, weekly, monthly, seasonal, and annual data can be taken into account, given its flexibility when comparing current data with the historical record of any specific period.
  Since only one variable is analysed, it is a simple and flexible methodology for many situations. Through clearly defined thresholds, current data are situated within a historical context and the drought situation can be recognized. It is useful in situations of humidity and drought. Since it gives the opportunity to examine different time scales and stretches, deciles can be used in situations of meteorological, agricultural and hydrological drought. As a weak point, shared by other indicators that only use precipitation, the effects of temperature or other variables during the development of the drought are not taken into account.

- **PNP**: The percent of normal precipitation (PNP) refers to the existing relation between the precipitation accumulated in a year and the annual average precipitation for a region during a given period, expressed in a percentage. Annual average precipitation is known as *normal precipitation* and is obtained from the average value of annual precipitations occurred in a period no shorter than 30 years.

Among the most used indices we can mention:

1. **PDSI**: A pioneering index is the *Palmer Drought Severity Index* (PDSI), which was developed in 1965 by Palmer and is based on the concept of water supply. It is an algorithm that allows to measure the loss of soil humidity. It is adequate for use in areas with uniform topography.
   The goal of the Palmer Drought Severity Index is to provide standardized measures of humidity conditions, in such a way that allows for comparisons between local conditions and these durations. Palmer developed criteria to determine when a drought or humid period starts and ends.

2. **SPI:** The Standardized Precipitation Index (SPI) was developed by McKee and other researchers in 1993. This standardized index allows the study of different timescales and is recommended for long-term records. SPI represents the number of standard deviations each precipitation record diverts from the historical average. Under this context, it can be deducted that the precipitation records over the historical average of the corresponding month will result in positive SPI, this represents humidity conditions; while precipitation records below the historical average of the corresponding month will result in negative SPI values, which indicates intensity in the humidity level. SPI stands out, among other characteristics, by its wide international dissemination.
   In spite of its multiple advantages, there is a series of disadvantages in its utilization, the most remarkable being: a) its difficulty of interpretation by the end user, and b) an incorrect characterization of the drought condition in arid and semi-arid environments (Ref. 1).

3. **DRI**: *Drought Risk Index* (DRI), which is formed by four components: annual average precipitation adjusted per the annual average temperature, seasonal rainfall, variability, and drought persistence. This index was defined to determine the severity and duration of the drought, and to predict the start and end of this period.

4. **NDVI**: *Normalized difference vegetation index* (NDVI), obtained through remote observations from radiometers installed in operative meteorological satellites. In a certain point of the image, the NDVI equals the difference of intensity of the light reflected in the red and infra-red range, divided by the sum of these

intensities, and its directly connected to the density of vegetation.

This index defines values of -1.0 to 1.0, where negative values are mainly formed by clouds, water and snow, and the near-zero negative values are mainly formed by rocks and bare soil. Very small values (0.1 or less) correspond to areas without rocks, sand or snow. Moderate values (from 0.2 to 0.3) represent bushes and grassland, while high values (from 0.6 to 0.8) indicate temperate and tropical forests.

Simply put, NDVI is a measure of the phytosanitary condition based on the way a plant reflects the light under certain frequencies (some waves are absorbed and others are reflected). This index is available to be used in real time, and it is regularly used all over the world in order to watch for droughts, predict agricultural productions, help predict fire areas and areas in the process of desertification. It is the preferred index for global monitoring of vegetation.

Predictability of droughts

The *skill* to forecast droughts tends to be limited to medium term, especially in the regions with lower impact of the global meteorological-oceanic phenomena, like El Niño –La Niña/Southern Oscillation (ENOS). Therefore, there is a marked interest in this issue: what could we do to improve drought forecasting? Or, what is the potential predictability of droughts?

Basically, *predictability* characterizes the “capacity of being forecast”, while forecasting *skill* characterizes “the ability to predict” (Ref. 7).

In recent years, a great effort has been made in the area of predictability of weather and climate phenomena (Ref. 5). Let’s make clear that by weather or temperie we refer to daily elements such as temperature, precipitation, wind or cloud cover, which change by the hour or daytime, while climate refers to the behaviour of the weather during long periods, usually 30 years (a statistical synthesis of weather).

Predictability is usually studied through the use of physical-mathematical models of the atmosphere. Why do we need physical-mathematical models? A collection, even a complete one, of the meteorological observations of all the surface and altitude stations, and of the operative satellites, would give us a current snapshot of the state of the atmosphere. In order to know what the weather will be tomorrow, we need a (physical-mathematical) model that simulates, based on the principles of Newtonian physics, how the atmosphere evolves. Moreover, the collections of these observations from different sources cannot show a complete, coherent image of the meteorological situation at a given moment. In order for this collection of observations to adjust in a coherent way to obtain a complete, global state of the atmosphere, the application of a model is needed.

The atmosphere is almost -but not completely- deterministic. Edward Lorenz, a meteorologist pioneer in the subject of atmospheric predictability and chaos, elaborated an image that illustrates well this situation: the butterfly whose wing-flapping a fortnight earlier changes the weather in remote areas of the planet. It is undoubtedly an indemonstrable metaphor, but it illustrates the processes that alter the forecasts and limit their utility.

The absolute limit of predictability of two weeks is a theoretical value; in practice, it is quite shorter, on the one hand, due to errors in the initial state and, on the other hand, due to the imperfection of the models. We can say that, at present, the most advanced numerical weather forecasting systems produce useful results for about a week. Forecasts for one to two or three days are very good or good; beyond that point they degrade little by little until losing all interest.

Is there any hope of going beyond deterministic limits? Yes, not only with the help of statistics, but also with the study of the long-term behaviour of the earth system (particularly, the interactions among its components: atmosphere, earth, oceans, ice, and biosphere). Even though promoters of “New Age” and postmodernism may not like it, physical laws keep applying (although, it is true, their causes may not be well understood).

From ten days on, the atmosphere has a macroscopically predictable behaviour: the seasons of the year and the climatic areas give testimony of phenomena regulating its general circulation. A typical example is the El Niño/Southern Oscillation (ENSO) phenomenon, already discussed, that brings into play interactions with oceanic circulation, much slower to evolve than the atmosphere. The weather regimes linked to El Niño have strong seasonal predictive potentials. Also, the sea temperature evolves slowly, and the models that connect the atmosphere to the ocean might give statistically useful prospects of up to one or two years. There are other phenomena of slow evolution that influence the weather regimes, such as soil humidity or the extension of snow fields.

The predictability of weather extremes (for example, drought) have received little attention. There are authors that find that predictability is higher than forecast skill, and that the gap between them shows an improvement margin, but others argue that there is no necessary relation between predictability and forecast skill. The inconsistency of these studies suggests that predictability and forecast skill can depend on the climate model used, the regions under study and climatic variables. Also, it is necessary to perform careful research to learn if the predictability of seasonal drought is linked to ENSO and how models represent that link. (Ref. 7)

Drought forecasting methods

In general, three types of methods have been used to forecasting droughts: statistical, dynamic and hybrid methods (Ref. 7).

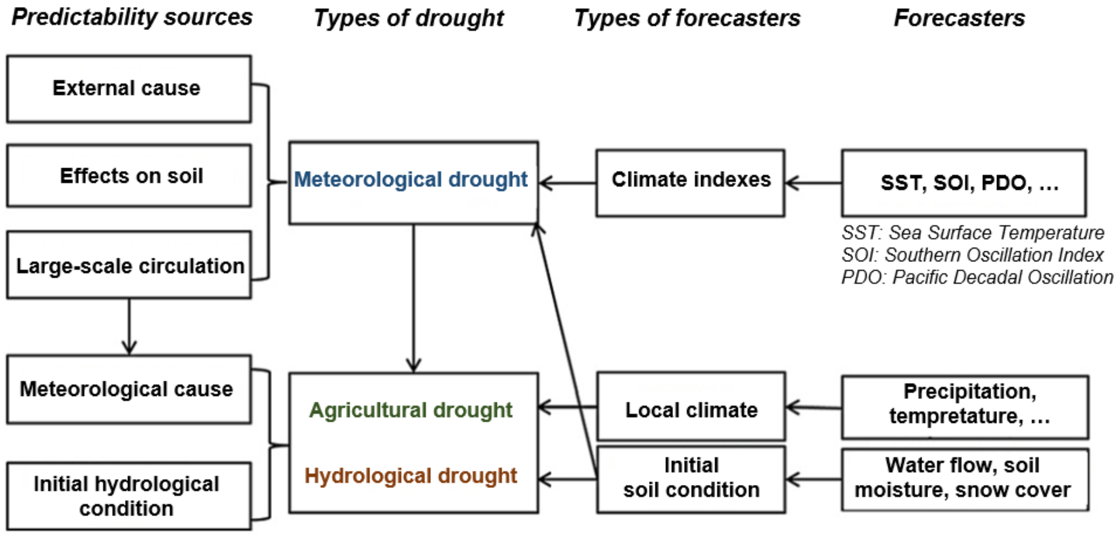
The statistical prediction method uses empirical relations of historical records, taking different factors of influence as predictors

With a higher computer capacity and a better understanding of the weather physic-dynamics, drought forecasting during the last few years has been addressed more often with state-of-the-art general circulation models (GCM), which provide a forecast based on physical processes of the atmosphere, the ocean and the earth surface.

The last decade has also witnessed the development of hybrid forecasting methods that combine forecast with both statistical and dynamic methods.

The statistical approach

For the statistical forecast, it is usually first identified a variety of predictors from the hydro climatic historical records (including the oceanic, atmospheric and earth component records) and then they are fed to different statistical models in order to forecast various types of droughts.



The previous figure (Ref. 7) presents the sources of predictability of various types of drought and the predictors of common use for the statistical forecast of droughts on a seasonal time frame.

Although predictors are generally obtained from historical observations (or reanalysis) that are already known before the forecasting period, with the current advances in weather and climate forecasting, predictors can also be obtained from the dynamic forecast for predicting hydro climatic variables.

In the surveillance and monitoring of droughts, besides the study of series of indices already mentioned, statistical methods are applied in order to estimate frequencies and return periods.

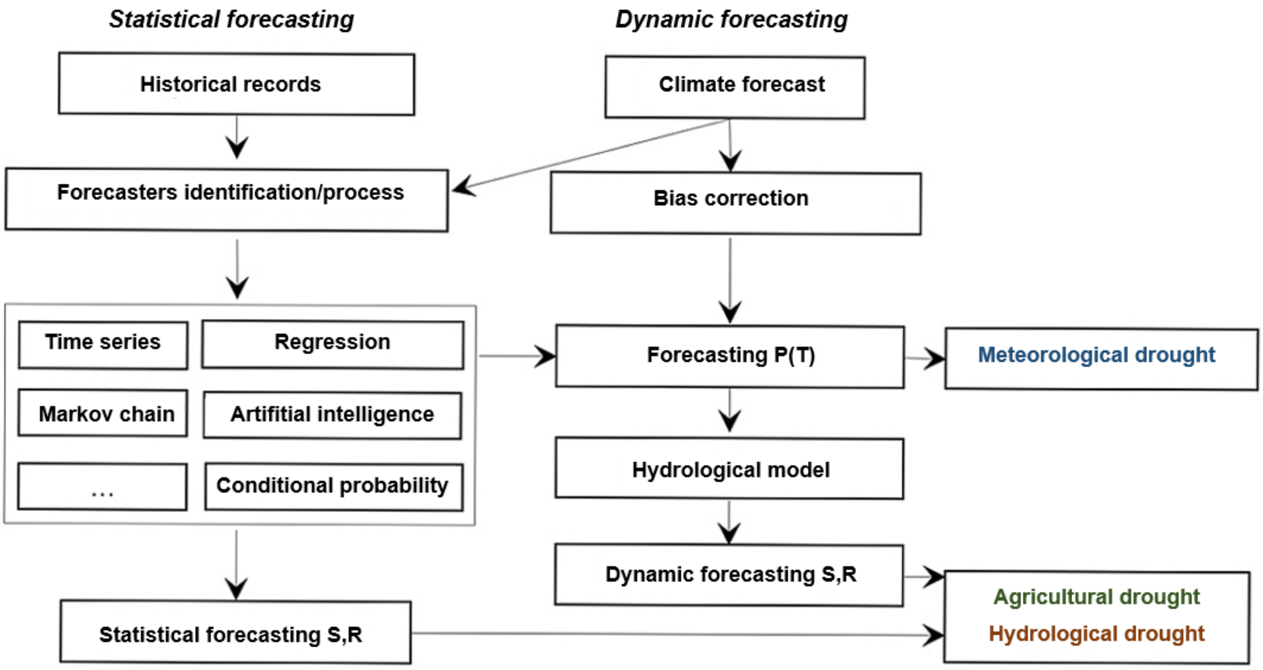
The dynamic approach

The dynamic approach for forecasting droughts is based on climate models and/or hydrological models that simulate physical processes of the atmosphere, the ocean, and the earth. Here, physical mathematical models previously described are applied. The dynamic forecast of hydrological and agricultural droughts in seasonal time frames is generally achieved on the basis of hydrological models guided by climate models, with certain forecasting skill, which depends both on climatic drivers as on the initial conditions.

Due to the coarse resolution of forecasts with climate models and their biases, post processing techniques and multi-model collections have been commonly used in order to enhance the forecasting skill.

Comparison of statistical and dynamical approaches

The following figure (Ref. 7) describes a schematic framework of the statistical and dynamic methods of drought forecasting (precipitation, temperature, soil humidity and run-off are abbreviated as P, T, S and R, respectively).



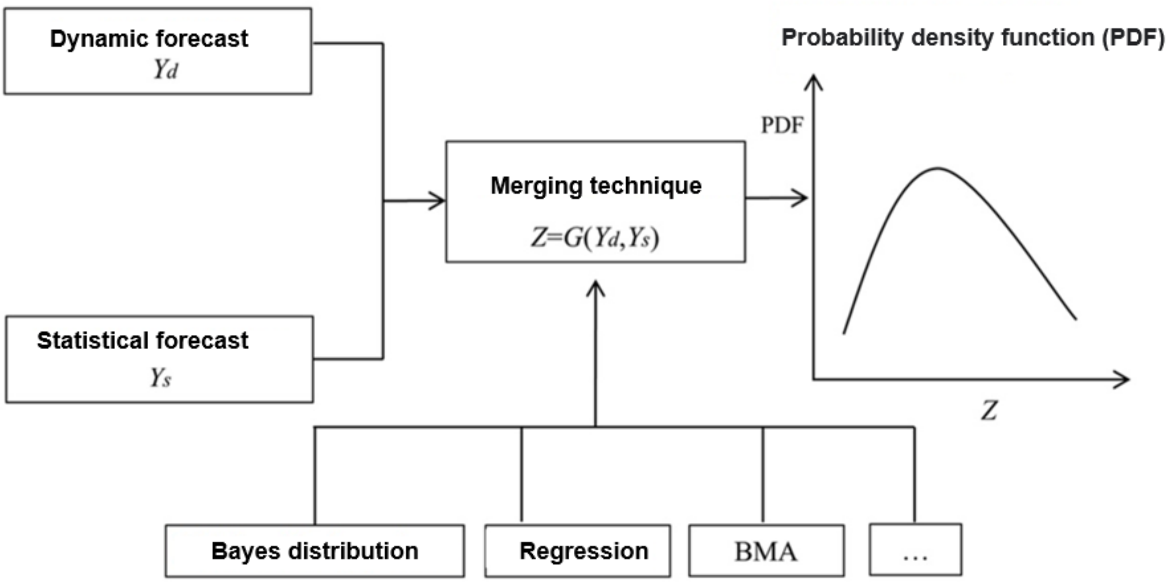
Generally, it is difficult to determine which method is finally the best, and the forecasting skills always depend on the season, the region and the forecasting period. However, there is a clear advantage of the dynamic methods over the statistical methods on the hydrological prediction if the precipitation forecast with physical mathematical models (GCMs) gives good results. Also, for the long-term forecast, the forecasting skill of the dynamic methods is generally higher than that of the statistical methods. When the forecasting skill of the weather forecast with dynamic models is low, statistical forecast can provide a useful forecast.

Several studies have shown that the two types of methods can complement one another. In general, statistical, and dynamic methods are complementary in forecasting drought (and weather) in the sense that a better understanding of the successful statistical forecasts can contribute to better dynamic models, and vice versa.

The hybrid approach

The statistical-dynamic hybrid forecasting of droughts implies, mainly, two steps: to calibrate the weather forecast to correct the bias (and the dispersion) of the physical mathematical general circulation models forecasts and combine it with forecasts from several sources.

In the following figure we can see a schematic framework of the hybrid forecasting of drought, which merges different forecasts (Ref. 7).



Schematic framework of the hybrid forecasting of droughts based on a Z drought indicator through the fusion of the dynamic forecast (Yd) and the statistical forecast (Ys) with function G.

The fusion or merging techniques commonly used, including the regression model, the Bayes posterior distributions and the Bayesian Model Averaging (BMA), can be used to reach a probabilistic forecast. The regression method can be used directly to incorporate multiple indicators of climate forecast and statistical forecast (or observations) with the aim of obtaining coefficients and parameters of each forecast in the form of a linear combination. The Bayes posterior distribution can be used to update the dynamic forecast with the previous distribution derived from the statistical forecast. Besides, the two types of forecasts can also be combined through Bayesian averaging in order to obtain the optimal weigh of each member so as to produce a unique forecast.

It has been proven that the hybrid statistical-dynamic method, based on the calibration, bridging and merging (CBaM) gives better forecasts of the climatic variables through the post processing of GCM results based on a Bayesian joint probability model (for calibration and bridging) and a Bayesian model averaging (for merging). For this method, the “bridging” represents the statistical forecast that uses the forecasts of the climate indices of the GCMs as predictors to produce alternative forecasts, and the “merging” is used to combine in an optimal manner the various forecasts.

In certain cases, the merging of a dynamic forecast with predictors obtained from observations in a statistical forecast framework is also called “hybrid statistical-dynamical forecast”.

During the last decade, hybrid statistical-dynamical has focused on Integrating the forecasting skill of both models. It has been proven that the best forecasts can be achieved through the combination of all the forecast sources to back up an informed decision-making. Given that the climate forecast calibration is an important component of hybrid forecasting, the development of new post processing techniques of climate and hydrological forecasting is an essential task in order to improve drought forecasting. Also, merging techniques of different forecasts of dynamical o statistical models must be researched more deeply in order to achieve an optimal combination.

The development of hybrid models of drought forecasting and the evaluation of their performance in various regions and seasons for different types of droughts might bring new opportunities to improve the forecasting capacity of these phenomena.

We would like to highlight, for example, the application by the European Centre for Medium-Range Weather Forecasts (ECMWF) of its Ensemble Prediction System (EPS) to the monitoring and forecasting of meteorological droughts using hybrid techniques. They have had some success, for example, in forecasting the dry conditions connected to La-Niña in September-December 2010 in the Horn of Africa, which were correctly forecast by the seasonal forecasts of the ECMWF as from June 2010. They continue to apply this approach for the European area (Ref. 6).

Prospects

There still are important challenges in the forecasting of droughts in the middle-to-long term, in a changing environment resulting from natural and anthropogenic factors. The prospects of research to improve the forecast of droughts include, among other elements, the assimilation of high-quality data, the improved development of models with key processes related to the occurrence of droughts, the optimal ensemble forecasting in order to select or weigh these ensembles, and the hybrid forecasting of droughts merging statistical and dynamical forecasts.

The use of artificial intelligence techniques, machine learning and deep learning also starts to be experimented in connection to droughts.

As we have already seen, droughts encompass a huge variety of temporary time frames, and it is important to improve prevision schemes that go beyond middle term (two weeks). There is, therefore, a growing interest of the scientific, operative and application communities in the development of sub seasonal to seasonal forecasts in order to provide an early warning of high-impact events such as floods, droughts, and heat and cold waves.

In order to close the existing gap between the mid-term meteorological forecasts and the seasonal forecasts, the World Meteorological Organization (WMO), within the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP), launched in 2013 a joint research initiative: the Sub-seasonal to Seasonal Prediction Project (S2S). The project tries to improve the forecasting skill and the understanding of sub-seasonal to seasonal time frames, with a special emphasis on high-impact climatic events, and to promote the adoption of the results by the operative centres, as well as their exploitation by the applications community.

Phase II of the S2S project started in January 2019 and will continue until 2023, including new ensembles of scientific sub-projects, as well as new operative research activities (Ref. 4), so that we have a certain hope that the knowledge on extreme event forecasting, particularly droughts, keeps spreading.

Effects of climate change

The weather of Earth has changed through history. During the last 650,000 years, there have been cycles of glacial advance and retreat, with the abrupt end at the end of the last ice age, about 11,700 years ago, which marked the start of the modern climate era and of human civilization. Most of these climate changes are attributed to very small variations of the Earth’s orbit, which alter the amount of solar energy our planet receives.

The current tendency to warming is of vital importance since it is extremely possible (with a higher than 95 percent probability) that most of it is the result of human activity since the middle of XX century, and it progresses at an unprecedented pace.

In the last half-century, the satellites that orbit the Earth and other technological advances have allowed scientists to have a global vision: they have collected many kinds of different information about our planet and its climate on a planetary level. This ensemble of data, collected through many years, reveals unequivocal signs of warming.

In the middle of the XIX century, it was proved that carbon dioxide and other gases called “greenhouse” trap heat. Their capacity to affect the transfer of infra-red energy through the atmosphere is the scientific basis of many instruments that have been put into orbit. There is no doubt that the rise in the level of greenhouse gases provokes that, as a response, the Earth warms up.

The ice cores extracted from Greenland, the Antarctica and the glaciers in tropical mountains show that the climate of the Earth responds to changes in the levels of the greenhouse gases. Also, ancient evidence can be found in tree rings, oceanic sediments, coral reefs, and layers of sedimentary rocks. This evidence of ancient climate or “paleoclimate” reveals that current warming is happening about ten times faster than the average warming rate that took place after the glacier ages. After the last Ice Age, carbon dioxide produced by human activity is rising at a rate more than 250 times faster than the one coming from natural sources.

The evidence of a rapid global warming that destabilizes the climate system is compelling (Ref. 15):

Rise of global temperature The average temperature of the Earth’s surface has increased approximately 1.18 degrees Celsius since the end of the XIX century, an unexpected change, largely driven by the increase of carbon dioxide emissions to the atmosphere and other human activities. Most part of the warming took place during the last 40 years, being the last 7 years the warmest. The maximum records were observed in 2016 and 2020.

Warming oceans: Oceans have absorbed a great part of this heat rise: the first upper 100 metres of the ocean show a warming of over 0.33 degrees Celsius since 1969. The Earth stores 90% of its surplus energy in the ocean. A key point is that oceans have, by far, the highest capacity of heat absorption of the climate system.

Thinning ice caps: Greenland and Antarctica's ice caps have had their masses reduced. Data from the NASA’s Gravity Recovery and Climate Experiment show that Greenland lost an average of 279,000 million tons of ice per year between 1993 and 2019, while the Antarctic lost approximately 148,000 million tons of ice per year during the same period.

Glacier retreat: Glaciers are retreating all over the world, which includes the Alps, the Himalayas, the Andes, the Rocky Mountains, Alaska, and Africa.

Reduced snow cover: Observations made through satellites reveal that, in spring, the snow cover of the Northern hemisphere has decreased during the last five decades, and that snow melts earlier.

Rise of the sea level: The level of the seas in the world has risen by approximately 20 centimetres during the last century. However, the rate in the last two decades has almost doubled the one of last century, and each year it is slightly faster. The only way for this to happen is because there is more energy coming into the system than going out it, and the main reason for this is that we are injecting CO_2 and other greenhouse gases to the atmosphere, which reduces the flow of long wave (infra-red) outgoing energy.

Reduction of the Arctic sea-ice: Both the extension and the thickness of the Arctic sea-ice have been rapidly reducing during the last few decades.

Extreme events: In recent times, it has been observed that the number of record-high temperatures has increased, while the record-low temperatures registered have decreased. Also, the occurrence of a growing amount of heavy rainfall events. This has been documented, for example, in the United States, since 1950.

Ocean acidification: Since the beginnings of the Industrial Revolution, the acidity of the oceans’ surface waters has increased by about 30%. This increase is the result of human beings emitting more carbon dioxide to the atmosphere and, therefore, the oceans absorb more of this gas. The amount of carbon dioxide absorbed by the upper portion of the oceans is increasing in about 2,000 million tons per year. The ocean has absorbed between 20% and 30% of the total of anthropogenic emissions of carbon dioxide in the last decades (between 7,200 and 10,800 million metric tons per year).

Global warming is, as we have seen, a reality that has been observed, measured and proven. We should avoid falling for new-age or post-modern siren calls that urge us to "not believe" in global warming or climate change for considering it a construct of the media to appeal to an audience eager for sensations, or a strategy of certain scientists to obtain higher funds or grants for their projects.

Should we worry about a rise in global temperature of 1.5 to 2.0 degrees centigrades in a century? If from winter to summer we go from about 10-15 degrees to 30-35, that is to say, a 20 degrees increase, why should we worry about one or two degrees?

These are two totally different situations. The first one results from a zero-sum seasonal recurring variation in and specific area or point. The energy earned during a season of the year is lost in the other one. In the second situation, it is the warming of a large part of the mass of the atmosphere. In the first five kilometres of the atmosphere there is 50% of the atmospheric mass. With an approximate volume of 1.28 10^{10} km^3 it results in a mass of about 1.62 10^{16} tons (16,200 trillion tons). In order to warm this exorbitant mass by one or two degrees, it is necessary to input into the system an enormous amount of energy, which provoke strong alterations in the atmospheric behaviour and, therefore, in the meteorological weather and the climate, causing the so-called "climate change" and even a severe impact on the global environment.

In climatology, the "climate change" is defined as a change in the state of the atmosphere that can be identified (for example, using statistical tests) by changes in the average and/or variability of their properties, and that persists through a prolonged period, typically decades or longer.

For the UN Intergovernmental Panel for Climate Change (**IPCC**), it refers to any change in the climate in chronological time, either due to *natural variability* or as a result of *human activity.* The IPCC is an original organization, with high-level scientists and representatives of the member countries, sponsored by the United Nations at the initiative of the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). Founded in 1988, its first report was published in 1990 and the last one, IPCC Fifth Assessment Report AR5, in 2013-2014. The next AR6 will be published in 2022.

For the UNFCCC United Nations Framework Convention on Climate Change (UNFCCC), climate change refers to a change in climate that can be attributed directly or indirectly to human activity, and that alters the composition of the global atmosphere and that is added to the natural climate variability observed in comparable periods of time.

Within the extreme events, we can highlight the ones connected to water availability: droughts and floods. Let's quickly review the recent high-impact extreme episodes of droughts (we will discuss Argentinian cases in the next part).

Recent American droughts have been the most prolonged in decades. In 2011, Texas experimented the driest 12 months in history. During the peak of the drought of 2012, an astonishing 81 per cent of the United States was under abnormally dry conditions, to say the least. The state of California experienced a particularly prolonged drought that stretched from December 2011 to March 2019, interrupted, in part, by the most humid winter ever experienced in the United States (Ref. 16).

In France, the last three years since 2018 (2018, 2019 and 2020), each one breaking records of drought, have made an impact on French society. It has affected regions that were seldom affected, such as the Grand East region. More frequent and more intense, these droughts have important impacts both on vegetation as on the soils (Ref. 10).

The Brazilian *pantanal* (marshland) recorded a severe dry season between 2019 and 2020. Local studies suggest that it was the result of a natural meteorological phenomenon, like the one that unleashed the water crisis in the state of São Paulo between 2014 and 2016, linked to a meteorological "lock", that provokes a reduction in the transport of warm, humid summer air from the Amazonia to this region. The situation also causes an increase in the risk of fires, that extends not only over agricultural areas but also over natural biome areas. The authors consider that these droughts by natural causes are suffering the effects of the climate instability and their impacts are therefore worse, since in the past there was not as much human occupation as there is now in the region and, for that reason, the population today is more vulnerable to the impacts caused by droughts (Ref. 4).

In the centre of Chile, since 2010 has prevailed an uninterrupted sequence of dry years, with annual precipitation deficits that range between 25 and 45%. Although intense droughts of one or two years are recurrent in this Mediterranean region, the current event is remarkable for its length and extension. The extraordinary character of this so-called "mega-drought of central Chile" was established by evaluating a century of regional precipitation records and with a reconstruction by analysing the rings of the trees (Ref. 12). The authors would like to emphasize that the mega drought happened mainly in neutral El Niño conditions (except for a year of La Niña in 2010 and the strong El Niño in 2015), in contrast with the cold conditions of the tropical Pacific, that often accompanied the dry years during the XX century. This suggests factors different from temperature of the tropical sea surface in the sustainment of the mega drought (for example, anthropogenic climate change).

Dendrochronology is the science that deals with the dating of tree rings in in woody trees and shrubs, by analysing spatial and time patterns of biological, physical or cultural processes. It has had great expansion in the last few years in the estimation of past climate (paleoclimate). In recent years, several articles have been published referring to studies of series of droughts applying this methodology. Multiple ensembles of observation data and reconstructions using data from tree rings confirm that human activities were probably affecting the global risk of droughts from the very beginnings of the XX century (Ref. 6).

We will describe the results of a very current article that we consider relevant. European researchers analysed 27,080 annual and dated measures of oxygen and carbon stable isotopes in tree rings of 21 living oaks and 126 relics (survivors) in order to reconstruct the summer hydro climate of Central Europe from 75 BC until 2018 AD. (Ref. 14). The reconstruction shows that the sequence of recent European summer droughts that started in 2015 is unprecedented in the last 2110 years. The authors suggest that this hydro climate anomaly is probably caused by the anthropogenic warming and the changes associated to the position of the summer jet stream.

Which would be the expected effect of climate change on droughts?

Climate change increases the probabilities of droughts to worsen in many parts of the world in the next decades. There are ways in which climate change can contribute to droughts: these dry phases can increase, rising the temperature and radiation. The higher temperatures can increase soil evaporation, making low precipitation periods drier than in colder conditions. Droughts can persist through a "positive feedback" were very dry soils and the reduced vegetation cover can suppress the rainfall even more in an already dry area. A changing climate can also alter the so-called "atmospheric rivers" (narrow corridors of moisture transported in the atmosphere), which can especially alter certain precipitation patterns. A combination of changing atmospheric rivers and warmer temperatures can also affect the snow cover in some regions, and cause their melting, potentially decimating water supply. Also, when soils and plants run dry, their lack of water content prevents their transference through evaporation that could cool down the atmosphere, which locally induces an additional warming of the air. This, in turn, provokes additional drying of the atmosphere: the so-called *snowball effect.*

The estimations of future changes in the seasonal or annual precipitation in a particular place are less safe for the estimations of future warming. However, on a global scale, scientists trust that the places relatively humid, like the tropics, and the higher latitudes will become more humid, while the places relatively dry in the subtropics (where most of the deserts of the world are located) will become drier (Ref. 16).

On a general level, the Special Report issued by the IPCC in 2019 (Ref. 8) includes several references to the expected changes in the thermal and water extremes.

Paragraph B.1: *Climate models forecast robust differences in the regional characteristics of the climate between the current moment and a global warming of 1.5°C, and between a global warming of 1.5°C and 2°C. These differences comprise a rise of the average temperature in most terrestrial and oceanic regions (high level of confidence), of extreme heat events in most of the inhabited regions (high level of confidence), of intense precipitations in several regions (medium level of confidence) and of the probability of drought and precipitation deficits in some regions (medium level of confidence).*

The report defines five reasons for concern (RFC), established in the IPCC Third Assessment Report, which provide a framework to summarize the main impacts and risks regarding the various sectors and regions. The second (RFC 2) refers to ***Extreme weather events:*** *risks or impacts for human health, livelihoods, assets and ecosystems from extreme weather events such as heat waves, heavy rain, drought and associated wildfires, and coastal flooding.* The impacts or risks connected to this reason for concern, based on the assessment of new literature that has been published, are estimated as *moderate to high* (serious and generalized impacts/risks) if the average global surface temperature increase reaches or exceeds 1.5 degrees centigrades.

As expressed in the Report, a great deal of these future estimations are obtained from simulations based on physical-mathematical models of the climate system. These models have greatly improved during the last few years, in part due to the enormous advances in computing, and also in the scientific knowledge of the behaviour of the earth system.

The last report by the IPCC Working Group I (scientific bases) assesses climate models in chapter 9. There have been substantial advances since the previous report in the assessment of model simulations of extreme events, although they recognize the difficulty in simulating clouds and their effect, and they admit that most models underestimate the sensibility of extreme rainfall to temperature variability or trends, especially in the tropics, which implies that the models can underestimate the forecasts of increased extreme precipitations in the future.

There is high confidence in the fact that the representation of the deadlock situations improves through increases in model resolution. As for droughts, it is worth mentioning that there are several definitions of drought and that the performance of the models can depend on the definition. At present, there is no comprehensive assessment of the group of climate simulation models for the case of droughts, although it is found that consecutive dry days simulated by these models are comparable to the observations in magnitude and distribution.

Impacts on Argentina

In high school Geography courses, we learn that in the Argentinian territory, the sub-humid, semi-arid and arid areas comprise about 75% of the total area, while the humid Argentina, the remaining 25%, mainly the "Argentinian Mesopotamia" and the humid Pampa, have adequate rainfall, enough to allow for cultivation without irrigation.

In the Pampa region it is located the highest percentage of the population, the economic capacity, and the power, and although the alternation of water extremes –floods or droughts– impacts severely on the region, those affect the arid Argentina as well. Floods and droughts are the hydro meteorological extremes of higher impact in Argentina.

Floods and droughts might cause damage to agricultural lands, affecting crops and food supply, with serious economical effects. Also, they can displace animals, such as rodents and snakes, leading to potentially dangerous conditions not only for humans but also for useful animals. Besides, sanitary risks increase, since water sources may be contaminated with toxic materials. A recent report by the World Bank about the "Impact of Climate Crisis on Poverty and the Argentine Macro Economy" (Ref. 33) reveals that, due to floods, there are average annual losses of assets between US$ 500 million and US$ 1400 million, that is to say, an average of US$ 1,000 million per year, and these losses could increase by 125% due to climate change.

Extreme droughts can also have important consequences for the environment, agriculture, economy, health and society. Although their effects can vary depending on the vulnerability of the region or population affected, the most common consequences are the decrease of agricultural production and of the capacity of loading livestock, malnutrition, dehydration, famine, massive migrations, damage to the habitat, erosion and eventual dust storms, social and alimentary conflicts. In a warmer world, the evaporation rises, which can cause that even humid regions are more prone to droughts. Several international agencies such as the Food and Agriculture Organization of the United Nations (FAO), the World Meteorological Organization (WMO), the Inter-American Development Bank (IDB), the United Nations World Food Programme (WFP) and the United Nations Educational, Scientific and Cultural Organization (UNESCO) develop activities and projects to help their members respond adequately to crises caused by droughts.

The United Nations Intergovernmental Panel on Climate Change (IPCC) is now in its sixth cycle of evaluation, during which they are elaborating the Sixth Assessment Report (AR6) with contributions from their three Working Groups and a Synthesis Report, three Special Reports and a refining of their latest Methodological Report. The Synthesis Report will be the last of the AR6 products, which will be released in 2022.

The contribution of the Working Group I -the Physical Science Basis- to the Sixth Assessment Report was presented on the past August 9th. This report addresses the most up-to-date physical comprehension of the climate system and climate change, gathering the latest advances on climate science and combining multiple lines of evidence of paleoclimate, observations, process comprehension, and global and regional climate simulations. Regarding the present situation, it confirms that "*Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation,* ***droughts****, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the Fifth Assessment Report (AR5)."*

It also expresses that *"Human-induced climate* ***change*** *has contributed to increases in* ***agricultural*** *and* ***ecological*** *droughts in some regions due to increased land evapotranspiration (medium confidence)",* human influence has likely provoked increases in the frequency of concurrent heatwaves and droughts on a global scale (high confidence), and that *"with every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely), and heavy precipitation (high confidence), as well as* ***agricultural and ecological droughts*** *in some regions (high confidence). Discernible changes in intensity and frequency of* ***meteorological droughts,*** *with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (medium confidence). Increases in frequency and intensity of* ***hydrological droughts*** *become larger with increasing global warming in some regions (medium confidence)."*

This report differs from the previous ones in that it includes discussions at a regional level. In the regions of our interest, the graphic with the synthesis of the change assessment observed in the agricultural and ecological drought indicates a "Low agreement with the type of change" and/or "Limited data and/or literature". Regarding this last point, it refers to the limited number of publications available in scientific networks.

In Argentina, the agribusiness sector, engine of its economic growth (during the 2010-2019 decade, it represented 8.7% of the GDP and an average 60% of the country's exports), is particularly vulnerable to droughts.

We will summarize some of their impacts according to Reference 17:

The serious drought suffered by Argentina at the beginnings of 2018 generated a fall of GDP of 2.5%, that added to the financial shock and the depreciation of the peso that occurred since April that year. The economic recession started during the second trimester, when the agricultural production fell by 32% per year due to the serious drought, and, from the point of view of demand, the exports fell over 8% (also per year). The drought of crop season 2008/2009, in a context of international financial crisis, also affected the prices of exports. In that occasion, the loss of production represented over 40% of the 2009 drop, which represented almost 80% of the recession. Besides the impact of droughts on the national income, they are very costly at a provincial level. Last year (2020), there was a very severe drought scene in a number of provinces.

In the following section, we will present a brief revision of publications and articles about the drought phenomenon in Argentina that were published in the past.

Historical revision

An obligatory historical reference is the publication of Florentino Ameghino's "*Las secas e inundaciones en la Provincia de Buenos Aires" (Droughts and floods in the province of Buenos Aires)*, 1884 (Ref. 34). Its subtitle summarizes a whole action program: *"Retention and not drainage structures".*

By studying floods and the means to avoid them, Ameghino highlights that "...this question is intimately connected to the issue of droughts, which from time to time take their toll on several regions of the province. *Moreover, I am convinced that all effort and work tending to avoid* ***one of those evils without taking into account the other*** *would probably cause more harm than benefit."*

It also quotes previous writings by Estanislao S. Zeballos, one of the most prominent intellectuals and politicians of the generation of the 1880s, who held three times the position of Minister of Foreign Affairs. About the Buenos Aires region, Zeballos, in 1876, expresses that *"In spite of its streams, lakes and rivers, this province suffers from awful droughts", "The solution to the problem of the drought is connected to this other very important issue: the convenient transformation of certain features of the land that permits the use of waters that today are pointlessly lost...", "to take advantage of the waters that flow to the Pampa lowlands and are lost in it; notwithstanding the general measures that I deem indispensable for fighting the drought and its effects".*

Ameghino follows those ideas, rejecting the simple and unlimited drainage of the lands, *"that will make the periods of great drought more intense, prolonged and disastrous"*.

Of course, this opinions from the mid-XIX century must be adjusted to current realities, but we are surprised by the global vision of the problem that these pioneers had in an environmental sense. If we review the current Master Plans of some provinces for different basins, we can see that a more engineering approach is applied and, in some cases, when bibliography is presented, the pioneering contribution of Ameghino is ignored.

We should note that in the neighbouring country of Uruguay, it is very common to perform small or middle-size engineering works that intercept and store runoff water, called "*tajamares*", as a method of water storage, animal trough, and also to avoid or to moderate the effects of drought. It is a response to the extreme variability and irregularity of the precipitation regime of that region, that produces a certain alternation of floods and droughts, sometimes extreme (to such an extent that it has been said that Uruguay is "*a dry country where it rains a lot*"). *Tajamares* are also built in Argentina and Paraguay.

The interest in droughts in our regions dates back to times much earlier than the generation of the 1880s. In Reference 19, the most outstanding cases of droughts in the Province of Buenos Aires in colonial times (in that work, floods are also discussed). Based on the documents from that time, it is found that the period 1600-1810 can be considered dry in general, with at least two sub-periods of very severe and prolonged droughts (1690-1708 and 1753- 758) and many brief droughts. Also, during period 1827-1832, there was an intense drought, known as "The Great Drought", where it rained so little that the vegetation completely disappeared, and fields turned into clouds of dust. The birds, wild mammals, cows and horses starved to death or died of thirst.

Researchers of the Environmental History Unit, **Institute of Human, Social and Environmental Sciences** (INCIHUSA, for its Spanish acronym) of the Regional Centre of Scientific and Technological Research (CRICyT, for its Spanish acronym), Mendoza, have published several very thorough and elaborate articles on the effects of climate on the colonial society, analysing a variety of historical documents and paying attention to hydrological extremes such as floods and droughts. In different periods going from the XVI to the XVIII century, they study the dry and humid sequences, and their extremes, in various Argentinian regions such as the North-East and the River Plate Basin, as well as in cities like Córdoba and Mendoza. To those interested in these periods, we recommend consulting Reference 20 that, although it deals specifically with the case of Córdoba, it contains information about other areas and includes very complete bibliography.

Another similar investigation about the effect of the climate of the colonial times in Argentina and Chile can be found in Reference 21. Although it is quite biased towards cold and rainy events, it also includes information about extreme dry periods.

An interesting historical study about the climate changes in the humid Pampa, based on the article that appeared in the "*Todo es Historia*" magazine, is presented in Reference 22. The authors, referring to the sequence of floods and droughts, affirm that "the climate was the determining factor of transcendental events, the one that really decided policies, battles, foundations... Becoming an ingredient of particular relevance in the idiosyncrasy of the Pampa". They reclaim the ideas of Zeballos and Ameghino, expressing that "If we continue with a simplistic policy of eliminating water with the indiscriminate opening of ditches and channels, it is because we do not consider droughts will be repeated.

Since the creation in 1872 of the Argentinian Meteorological Office, today called National Weather Service, during the presidency of Domingo F. Sarmiento (one of the first meteorological services in the world), an age of systematized meteorological information starts, with data from stations with specific instruments, and methodical measurement of variables and meteorological elements. For the city of Buenos Aires, for example, there are systematic records since 1876. In the following section we will identify the most recent works on droughts produced during these instrumental period, complemented since the decade of 1970 with remote measurements installed in satellites.

We will close this section by remembering Engineer Juan Jagsich, Professor of the University of Córdoba in the first decades of the last century, of Croatian origin, graduate from the Polytechnic Federal School of Zurich, a centre of excellency that generated several Nobel prizes. This solid education explains its extremely prolific scientific production, encompassing, in particular, Topography, Cartography, Geodesy, Astronomy, Meteorology, Climatology and Oceanography. In his notes on South American climatology and long-term forecast, he introduces concepts of turbulent movements, oceanographic phenomena like El Niño, and the influence of great disturbances of the general atmospheric circulation, like anticyclones. It is remarkable that these relatively advanced or novel concepts for his time were published on several articles in the Buenos Aires newspaper "La Prensa" since the mid-1920s until the late 1930s. As for droughts, we highlight the articles published in "La Prensa" in 1929 (Ref. 23) and 1936 (Ref. 24), where Jagsich shows the importance of the atmosphere-ocean interaction in the generation of atmospheric fluctuations that would generate periods of rainfall or drought over the continents. We are surprised that these subjects, which would be consolidated on the academical field two or three decades later, have been included in such early years in a mass-circulation newspaper.

What do we know about droughts in Argentinian regions?

In recent years, the drought phenomenon has attracted the attention of local media because of the intensity of its latest occurrences in Argentinian regions and its strong socioeconomic impacts.

In the last few years there was, and presently is, an intense research activity on these hydrological extremes in Argentinian regions by meteorologists, climatologists, hydrologists, geologists and agronomists, among others. Their study, analysis and interpretation is of the utmost importance since, if we are aware of the real or potential threats of these phenomena, we will be in a better position to prevent or mitigate them.

It is clear that droughts are having a strong impact on Argentina. Which is the level of that intensification? How are they regionally distributed? How did they evolve? In order to guide readers to respond these questions, we include a bibliographical list with the publications and articles of the last few years in specialized literature. It is not comprehensive, but we have chosen the contributions that we found more relevant. Readers will probably be able to identify other cases referred to their region or period of interest by consulting the bibliographical references of the different articles quoted.

The references are presented, where possible, in chronological order, starting by the most recent ones, and geographical order, starting by the ones that deal with regional or national aspects, continuing with provincial ones and finally, with local or specific ones.

- *Reference 17 (2021)*: A recent report by the World Bank, quoted in the previous section, titled "Floods and droughts, the climate risks that affect Argentina the most". As for the macroeconomic impacts of droughts, it indicates that "they have turned to be very expensive for Argentinian economy, and could even be much more in the future if climate change-induced droughts reduce the agricultural yields more severely and often than in the past".

- *Reference 25 (2021):* In April this year, the UNESCO organized a four-day training seminar in Montevideo about the subject "Characterization, monitoring and nature of droughts", whose general goal was to increase and standardize knowledge on the causes and modes of droughts, and to make known the different tools available for monitoring and estimation of their frequency and intensity. The presentations of the course, prepared by experts from the Water Centre for Arid and Semi-arid Zones of Latin America and the Caribbean (CAZALAC, for its Spanish acronym), are available online, and are very complete, clear and broad. There are four units that cover the following subjects: *"Natural and anthropic causes of drought", "Impacts of droughts in Latin America and the Caribbean", "Monitoring of the meteorological and hydrological drought conditions"*, and *"Vulnerability to drought"*. It is an essential reference to everyone who wants to have an up-to-date and complete overview on the subject, and we recommend their reading.

- *Reference 26 (2020):* Chapter on *"Floods and Droughts"* of the RIOCCADAPT Project of the Ibero-American Network of Climate Change Offices (RIOCC, for its Spanish acronym), whose goal is to identify, review and assess the actions of climate change adaptation being carried out in the IOCC countries. The chapter includes several discussions and information about droughts in Argentina.

- *Reference 27 (2019):* It presents a new global database of meteorological droughts during period 1951 to 2006, considering three spatial scales: global (0.5°C), macro regional and national. The study analyses 23 macro regions, based on the ones defined in the Fifth IPCC Report, and includes the ones of the most interest for us: the Southern South America (SSA).

- *Reference 28 (2019):* It discusses the correlation between global warming and some indices of drought in tropical and subtropical regions. It concludes, among other points, that global warming might be contributing to the drying process of subtropical regions in 25% of the regions analysed, while 58% shows an oscillation that prolongs through the XX century, end of the XIX century and beginnings of the XXI century.

- *Reference 29 (2006)*: Book "*"El Cambio Climático en la Cuenca del Plata"* (Climate Change in the River Plate Basin). It is a very thorough and comprising text that also includes several references to droughts in the region. An important reference about the subject at that time.

- *Reference 30 (2015)*: It discusses the utilization of the El Niño-Southern Oscillation (ENSO) as a tool for the regional monitoring of droughts in Southern South America (SSA). A conclusion to highlight: "Part of the central region of Argentina registered increases in the accumulated precipitation values during the second half of the XX century, which was favourable for an expansion of the agribusiness frontier. *However, considering the reversal of the precipitation trends from the beginnings of the decade of 1980 and beginnings of the decade of 1990... and its condition of having a threat of higher droughts, it is recommended to realize contingency and mitigation plans for droughts in order to reduce their impacts, mainly at the agricultural level."*

- *Reference 31 (2015):* The spatial distribution of the drought threat in Southern South America using a drought threat index, and indicator recently proposed that is based on the spatio-temporal characteristics of the standardized precipitation index. The drought threat map was obtained in 3 and 12 months timescales, for period 1961-2008, and allowed to identify regions under low, moderate and high threat.

- *Reference 32 (2020)*: A recent document by the UN Office for the Coordination of Humanitarian Affairs (OCHA) that pretends to promote a discussion about the humanitarian dimension and consequences that droughts have, among other factors, on the populations that inhabit the North of Argentina, limitating their capacity of food supply for the population.

- *Reference 33 (2018):* A preliminary work that the School of Economy and Business of the National University of San Martín (UNSAM, for its Spanish acronym) presented in March 2018 to estimate the economic loss in the soybean crop generated by the drought that was affecting he main agricultural productive area of the country.

- *Reference 34 (2018)*: A study of the precipitation pattern during the La Niña event 2017/18 in San Luis. They find that "This drought was the second highest of the last ten years in San Luis".

- *Reference 35 (2017)*: A technical article on the recurrence of droughts and floods in Argentinian plains published by the National University of Lomas de Zamora. Following Zeballos and Ameghino, the author considers that "The solution to the problem of droughts and floods must not be considered in isolation, but we should try it to be an integrated one, and that this two-tier scourge of nature cancels itself out or that its destructive effects decrease.

- *Reference 36 (2020)*: A technical article by Córdoba National University that studies hydrological droughts in 14 hydrographic basins of Argentina in the rivers Colorado, Mendoza, San Juan, Atuel, Ctalamochita, Anisacate, Xanaes, Suquía, Dulce, Juramento, Salado, Paraná, Bermejo and Pilcomayo. They find that "*simultaneous and multi-annual hydrologic droughts occurred in all basins, registered in periods 1967-1971, 1945-1952 and 1936-1939".*

- *Reference 37 (2014)*: *Atlas de Sequías de la República Argentina (Drought Atlas of Argentine Republic)* published by the Centro de Relevamiento y Evaluación de Recursos Agrícolas y Naturales CREAN, UNC-CONICET, available in https://www.crean.unc.edu.ar/atlas-de-sequias-2/

- *Reference 38 (2012)*: Study on the temporal and spatial variability of droughts during period 1955/2009 in the province of Chaco, based on a series of precipitations obtained from provincial and national statistical sources, and data obtained from measurements from 19 rain gauges. It is concluded that this phenomenon is a constant risk in that province.

- *Reference 39 (2010):* The probable physical causes of droughts in the Southern sector of South America (South of 20ºS) through indices of monthly and annual climate drought in six regions of this area and their connections to seventeen predictors. They highlight that *"the relevance of the ENSO cycle is inferred from the development of predictability during fall-winter and its interaction with the evolution of the continental depression during spring, reaching maximum predictability in November-December"* and that *"the humid Pampa leads the group of indices of regional drought in six consecutive months (August-January), a period of great seasonal importance for the great grain harvest in the country".*

- *Reference 40 (2009):* Study on droughts in the province of Buenos Aires during period 996–2007 from precipitation data corresponding to 33 meteorological stations that cover the area of the province of Buenos Aires and data about drought risk provided by the Ministry of Agricultural Affairs of the Province. They analyse the phenomenon from the meteorological point of view, that is, as a significant decrease in precipitations, and then proceed to research on the direct and indirect consequences of drought in order to classify them according to type of drought: meteorological, agricultural and hydrological.

- *Reference 41 (2015):* Study that addresses drought as a product of social vulnerability, consequence of poor management and lack of foresight by the affected agricultural producers. The occurrence of droughts in the districts that constitute Buenos Aires South-West during 2001-2006 is studied. The work discusses *at length* the impact on different crops (corn, wheat, sunflower, soybean), as well as the current legislation regarding drought and the Development Plan for the South-West, that identifies the urgent need to implement integrated solutions in order to counteract the limitations of the region.

- *Reference 42 (2009):* A study about droughts in three towns of the Eastern agricultural region of La Pampa province: General Pico, Santa Rosa and Guatraché, for period 1921-2009.

- *Reference 43 (2007)*: A study of the impact of droughts on the productivity of corn in the humid Pampa during the last century, using monthly rainfall data of the towns located in the Argentinian humid Pampa, which include the South of Santa Fe province, the province of Entre Ríos and the province of Buenos Aires during period 1903-2001. Some conclusions: *“In the long-term trends of seasonal precipitations, it can be noticed a growth bias of summer precipitations and the opposite in winter precipitations”*, *“If we filter the large-scale effects, we can see the importance of the productivity falls that happened during the La Niña droughts of 1988-89 and 1995-96. This also shows how important both droughts were in order to make productivity fall in the last two decades, although being concealed by possible technological effects.”*

- *Reference 44 (2007)*: Study that tries to discover the influence exerted on the precipitation variation, in a mediterranean region such as the Argentinian Northwest, the thermal fluctuations of the surface waters of the flanks of the Atlantic and Pacific oceans. They find out that regional droughts of the Argentinian Northwest are related, preferably, to thermal anomalies of the coastal oceanic waters.

- *Reference 45 (2006)*: Work that tries to elucidate if the marked shift West experienced by the agricultural frontier from the decade of 1970 onwards constitutes an irreversible change in the precipitation regime or it is part of a long-term cycle, with dry and humid phases, separated by transition phases, that is, if the precipitation regime is adjusted to a linear or cyclic evolution. It presents arguments to validate both hypothesis (we assume that the acceleration of global warming at the beginning of the century, which provoked a strong rise in intensity and frequency of extreme events, suggests that the hypothesis of permanent change -the most accepted by the specialized community- is the most plausible one).

- *Reference 46 (1997):* An evaluation of the extreme droughts in the Argentinian Pampa region for the periods 1931/1960 and 1961/1990. They used monthly precipitation and potential evapotranspiration data from 28 meteorological stations located in the provinces of Buenos Aires, Santa Fe, Córdoba, La Pampa and Entre Ríos, calculating the water balance and Palmer’s drought index. In one of the conclusions, it expresses that “... *it has been proved that extreme events happened at the beginning of the decade of 1970 and that in later decades there is a declination in the severity of droughts.”* This affirmation should be revised in the light of recent observations.

- Reference 47 (2004): Study on the temporal evolution of the Palmer index in the city of Villa Mercedes, San Luis, during period 1903-2003, using meteorological data from Villa Reynolds Meteorological Station, the Agro-meteorological Station of the Agricultural Experimental Station of INTA San Luis and the Water Directorate of the Government of San Luis province, and useful water calculations for the soils of the area up to a meter deep, their retention capacity being 150 mm. They find that “*We can conclude that in the last 33 years (1970-2002) droughts decreased in frequency and intensity, but this trend has recently reversed with a*

prolonged drought during 2003, which reached an intensity never observed during the last century. The current drought (n.b. 2004) *in the area under discussion is of the highest intensity in the last 100 years".*

From this abundant bibliography we can conclude that in Argentina, droughts occur in many and diverse regions of the country; that in some of them (for example, in the province of Buenos Aires) they are a recurring phenomenon; that there is a certain predictive skill, considering some tele-connections; that in some extreme cases they have strong socioeconomic impacts; and that an increase in their intensity and frequency is expected due to global warming.

Final comments

The Argentine Republic covers an extensive territory that presents very diverse climates and biomes. However, the drought phenomenon is presented, in very different degrees and periods, almost all over the country. As we have seen, from estimations that emerged from scientific research, although climate variability is often the main cause of individual events of the droughts, the occurrence of severe cases during recent years in many regions is consistent with results derived from forced simulations with rises in the concentration of greenhouse gases, and therefore it is expected that these phenomena continue to intensify in the immediate future.

We have tried to give information and spread concepts about this hydro-meteorological extreme for its use by the communities that suffer its consequences, including notions about: its definition and characteristics, some indices and indicators for its monitoring, its predictability and the forecasting methods, and its behaviour in several regions of the country. We hope that they have been useful.

As we have seen, given its complexity and the variety of actors and areas where it impacts, to face or mitigate drought with a certain level of success it is necessary a series of actions to improve its management, which can include: its identification, monitoring, early warning and eventual forecasting through the use of products elaborated by specialized centres or institutions; the building of water storage structures during rainy seasons for their use in dry periods; the hiring of specific insurances; the planting of varieties of seeds that are drought-resistant and, as suggested by the World Bank, the application of tax policies that allow the producers to absorb and overcame the impacts of this extreme phenomenon.

Recently, the FAO and the Inter-American Development Bank (IDB), have published guides about strategies and policies to manage droughts, giving practical guidance in terms of planning and management for better coping with them. In year 2020 the FAO released *"Early Warning – Early Action plans on agricultural drought"* (Ref. 32) and this year the IDB published a policies report (Ref. 33) where they analyse the water crises produced by droughts in Spain (including the Canary Islands), Chile, Mexico, Honduras dry corridor, Guatemala and El Salvador, Brazil and South Africa, exploring facts and common mistakes in the response mechanisms, and extracting valuable lessons to help policymakers deal with droughts.

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