1

Understanding the impact of climate change on water resources

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Defining climate and the influential factors

According to the World Meteorological Organisation, the climate may be defined as the mean conditions prevailing in a given place (temperature, precipitation, etc.) and calculated on the basis of observations over at least 30 years. A climate is characterised by mean values, but also by variations in values and by extremes. For the planet as a whole, the climate is the result, over space and time, of a vast series of interactions between the elements making up the following compartments:

- atmosphere;
- lithosphere (crust of the Earth);
- hydrosphere (all seas, oceans, lakes and rivers on the planet);
- cryosphere (surfaces covered with snow and ice);
- biosphere (all living things).

The balance of the energy exchanges between these compartments depends on a number of factors.

The first is the quantity of solar energy reaching the Earth. The planet is subject to periodic variations of its axis and orbit that modify its position with respect to the sun and consequently the quantity of solar irradiance received (see Figure 1). These variations are called the Milankovitch cycles and they explain in part the progressive shifts in glacial-interglacial cycles that have characterised climate regimes over the past several million years (Lisiecki and Raymo, 2005; Jouzel *et al.*, 2007). These cycles is consequently very long, ranging from 10 000 to 100 000 years.

However, orbital forcing explains only part of the climate variations. The properties of the various compartments, e.g. atmosphere, oceans, cryosphere, and their complex interactions play the dominant role in the amplitude and frequency of the glacial-interglacial cycles (Sigman and Boyle, 2000; Jouzel *et al.*, 2007), notably by influencing the fraction of the solar irradiance reflected by the planet. This fraction, which varies depending on the darkness of the planet surface, is called albedo. The factors contributing the most to albedo are, in the atmosphere, clouds and aerosols (particles suspended in the air), and, in the lithosphere, the type of terrestrial surface (bare ground, vegetation, ice). The climate also depends on the concentration of the greenhouse gasses (GHG) present in the atmosphere (see Figure 1). GHGs, i.e. water vapour, CO_2, ozone, methane and nitrous oxide, are naturally present in the atmosphere. They absorb part of the radiation emitted by the Earth (causing the lower layers of the atmosphere to warm) and re-emit part of the radiation to space. When the concentration levels of GHGs increase, a greater percentage of the infrared radiation is trapped in the lower layers of the atmosphere, resulting in low-altitude warming.

Figure 1

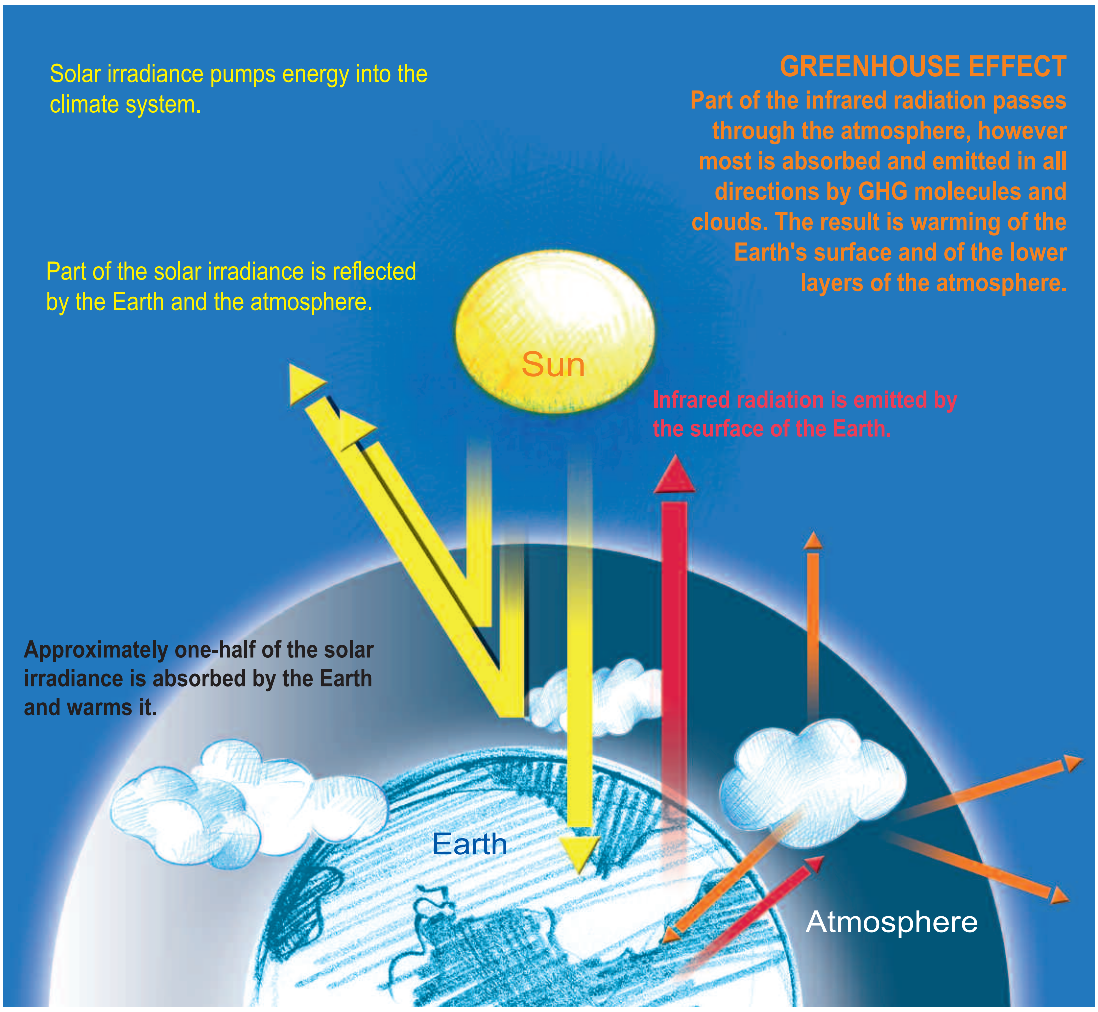

Diagram showing the functioning of the greenhouse effect as part of the radiation balance in the climate system (according to IPCC, 2007).

Other phenomena also influence the climate. Examples are El Niño and La Niña, two phenomena caused by disturbances in the atmospheric circulation between the poles and the equator, themselves caused by variations in ocean temperatures. El Niño occurs when the precipitation zones move eastward in the Pacific Ocean and block the current of cold water that otherwise moves north along the coast of South America. Conversely, La Niña occurs when the trade winds in the Pacific Ocean strengthen and push the warm surface waters away from the coast of South America, thus reinforcing the current of cold water. In both cases, these atmospheric phenomena cause severe cyclones and dry periods on either side of the Pacific Ocean and even on the global scale. In the same manner, the large-scale cyclical variations in the atmospheric and ocean currents of the Atlantic Ocean also influence the climate. Two are of particular importance, the North Atlantic Oscillation[1] and the Atlantic Multidecadal Oscillation[2].

Major ocean currents also affect the climate by contributing to the redistribution of heat. For example, the Gulf Stream is a current that starts in the region between Florida and the Bahamas and travels northward to Greenland. It play a role in regulating winter temperatures in Western Europe. However, in recent years, its importance has been downplayed by scientists (Seager *et al.*, 2002).

1. The North Atlantic Oscillation (NAO) index is based on the difference of normalised sea level pressure (SLP) between two meteorological stations, Gibraltar and Reykjavik.
2. The Atlantic Multidecadal Oscillation (AMO) index is calculated by averaging sea-surface temperatures in the Atlantic Ocean north of the equator.

Finally, the climate is influenced both directly and indirectly by feedback phenomena that can amplify or attenuate the initial effects of the phenomena mentioned above. One example of a positive (amplifying) feedback is that occurring when rising temperatures melt snow and ice. The worldwide reduction in snow-covered areas means there is an increase in darker surfaces (land and water) that trap more of the heat emitted by the sun (see Figure 2). Water vapour is also involved in a positive feedback loop. The increase in temperatures augments the quantities of water vapour in the atmosphere, which in turn increases the greenhouse effect. Finally, liquid water, notably that contained in clouds, can contribute to both cooling the atmosphere by reflecting solar rays back out to space (primarily high cloud formations) and to warming the atmosphere by trapping the infrared radiation rising from the surface (primarily low cloud formations).

Figure 2

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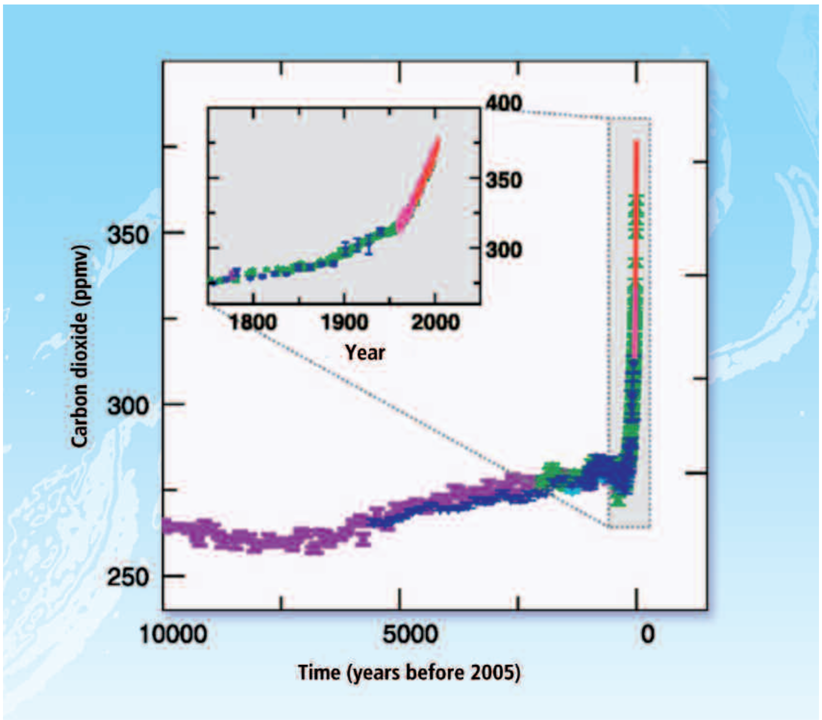
Dark surfaces revealed by melting snow trap more heat and accelerate the melting process.

Causes and consequences of climate disruption

Human activities are the cause of growing emissions of greenhouse gasses (GHG). Over the past millennia, CO_2 concentrations in the atmosphere stood at approximately 280 ppmv (parts per million by volume), then jumped from 280 to 385 ppmv between 1800 and the years just after 2000 (see Figure 3).

Figure 3

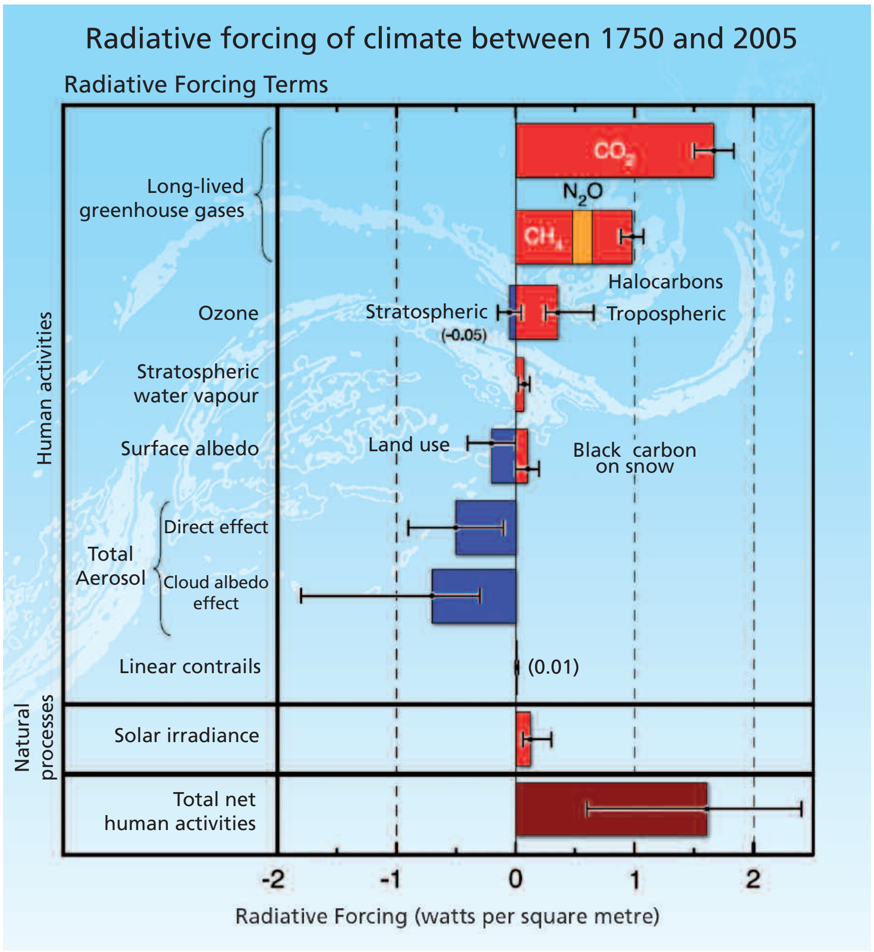


Atmospheric concentrations of CO_2 over the past 10 000 years (large graph) and since 1750 (detail). The data are drawn from ice cores (the different colours represent different studies) and from direct atmospheric measurements (red lines) (IPCC, 2007).

Transportation and industry (including the production of halogenated compounds) are the main human activities releasing GHGs, however agriculture (clearing of forests, nitrous oxide from nitrogen fertiliser, methane from the digestion of ruminants) also contributes non-negligible quantities (see Figure 4).

As explained in the previous section, the increase in GHG concentrations modifies the radiation balance in the atmosphere (see Figure 4), which in turn, strictly according to the laws of physics, results in an increase in atmospheric temperatures and changes in evaporation rates, in atmospheric humidity and in condensation processes.

Figure 4



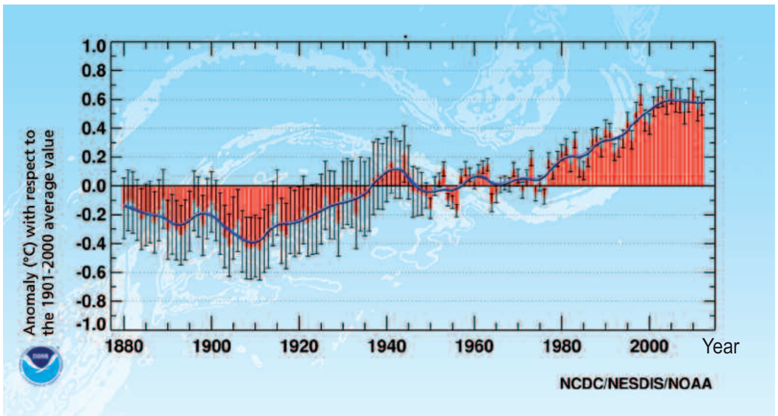
Summary of the principal components of the radiative forcing of climate change (IPCC, 2007). Positive forcings lead to warming of the climate and negative forcings to cooling. Note that black carbon is produced by incomplete combustion of solid or liquid substances such as fossil fuels, biofuels and biomass. When it lands on snow, the black carbon modifies the albedo and more heat is drawn from the solar irradiance. Linear contrails are the long, thin lines of condensation that sometimes form behind aircraft. They reflect solar irradiance and absorb infrared rays. By increasing cloud cover, they are the cause of slightly positive radiative forcing.

Observation of climate variables (temperature, precipitation) over the past decades has revealed major changes of the types mentioned above that have affected the water cycle (evapotranspiration, runoff, groundwater) and water quality (temperature, chemistry).

Observed impact on atmospheric temperatures

Over the past century, the globally averaged surface temperature has risen rapidly, as shown by the terrestrial temperature measurements carried out over the past 150 years (see Figure 5). Between 1951 and 2010, the globally averaged temperature rose 0.6°C (IPCC, 2007). The average speed of the temperature rise over the past 50 years was virtually double that of the past 100 years. As a result, the last 12 years (2001-2012) were among the 14 hottest years ever recorded since 1880 (NOAA, 2012).

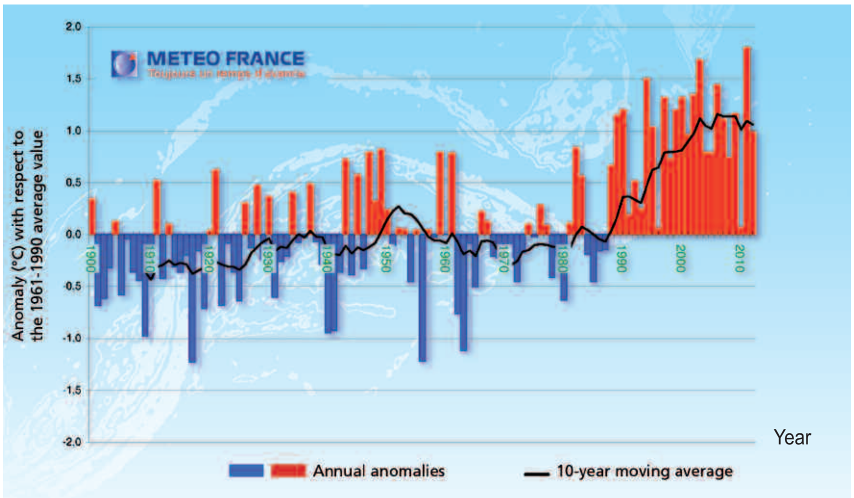
Figure 5



Change in the globally averaged surface temperature, on the basis of data compiled by the National Oceanic and Atmospheric Administration (NOAA), © NCDC: Global Surface Temperature Anomalies. The Y-axis shows the difference in °C over the period 1880 to 2012, with respect to the long-term average value calculated for the period 1901 to 2000.

The change in temperature has also been noted on a more local scale. Over the last century, the average air temperature in continental France increased by approximately 1°C, the increase being greater in the southern than in the northern section of the country (Soes, 2011; see Figure 6).

Figure 6



Change in the anomaly of the averaged annual temperature in France over the 1900s, with respect to the long-term average value calculated for the period 1961 to 1990. The averaged annual temperature is defined as the average of the averaged annual values of the daily minimum and maximum temperatures. The anomaly is calculated by comparing the averaged annual temperature to the 1961-1990 value. Negative anomalies are shown in blue, positive anomalies in red. This graph was plotted using homogenised data series spanning the 1900-2012 period and distributed over continental France (Météo-France, 2012).

The increases in the minimum temperatures (1.2°C) are greater than those in the maximum values (0.6°C) (Moisselin *et al.*, 2002). Analysis of the data series by Météo-France for the period 1951 to 2000 also revealed higher temperatures during the day and at the end of the night, as well as a reduction in the number of days with freezing temperatures (Dandin, 2007).

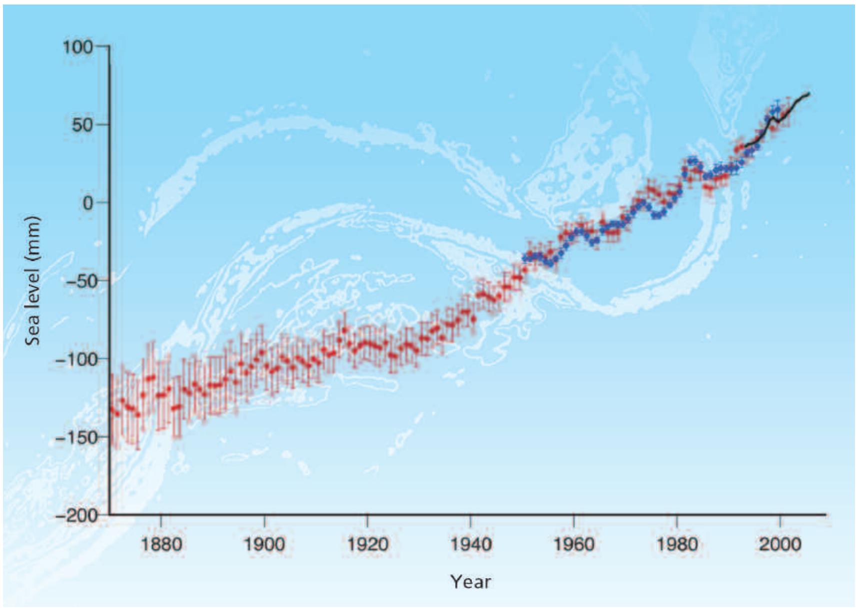
Observed impact on precipitation, the cryosphere and sea levels

Climate change impacts precipitations in two distinct manners. The rise in temperatures means the air can hold more humidity which in turn has an influence on the frequency and intensity of precipitation. Secondly, because the rise in atmospheric temperatures is greater at the higher latitudes, the thermal gradient between the poles and the equator is reduced, which modifies atmospheric circulation, winds and the entire hydrological cycle.

These hypotheses have been confirmed globally by an analysis of the data series covering the second half of the last century. Subtropical zones now tend to be dryer whereas an increase in precipitation has been observed at the low latitudes.

In addition, surface areas covered with snow and ice have decreased year after year (again due to the increase in temperatures). Snow-covered areas in the northern hemisphere decreased by 7.5% over the 1992 to 2005 period, following a sudden and sharp transition between 1986 and 1988 (Brown, 2000). Similarly, satellite data (since 1978) have revealed that the averaged annual surface area of the Arctic Ocean covered by ice has dropped by approximately 2.7% per decade, with even sharper decreases of 7.4% during the summer period (Comiso, 2002, 2003). Melting of the ice pack has led to an increase in the average sea level, up 1.8 mm per year on average since 1961 and 3.1 mm per year since 1992 (Church and White, 2006; see Figure 7).

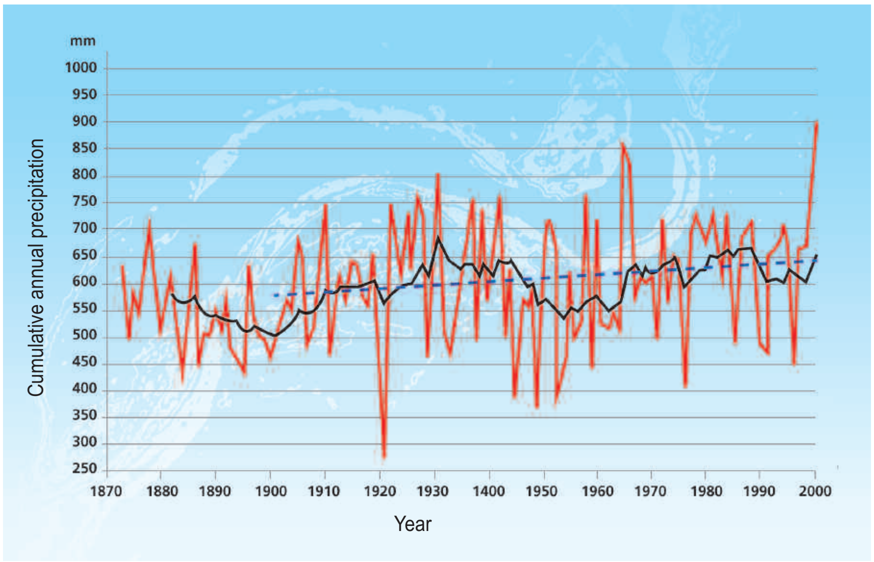
Figure 7



Globally averaged annual sea level based on reconstructed zonal data (red), tide-gauge data (blue) and satellite data since 1992 (black). Sea levels are measured in millimetres and compared to the 1961-1990 average value. The error bars are set to 90% of the confidence intervals (IPCC, 2007).

In France, the trend is not always clear and may be contradicted by data from the southern section of the country, however on the whole, there is an increase in annual precipitation (Moisselin *et al.*, 2002; Dubuisson and Moisselin, 2006; see Figure 8).

Figure 8



Cumulative annual precipitation (in mm, red line) in Paris from 1873 to 2000 (Moisselin et al. *2002). The black line is a 15-year moving average. The dotted blue line is the trend from 1901 to 2000.*

An increase in seasonal differences and greater regional diversity have also been observed. For example, in the northern section of France, precipitation has tended to increase in the winter and to decrease in the summer (Dandin, 2006, 2007). In addition, dry periods during the summer are increasingly frequent and intense (Dubuisson and Moisselin, 2006).

On the other hand, no clear trends in extreme events have been detected due to the lack of long data series on the subject and the great spatial variability of precipitations in France. The indices characterising events producing high daily precipitation values do not all point in the same direction. However, it has been noted that the number of days with heavy precipitation (> 10 mm) has risen over the two northern thirds of France (Dubuisson and Moisselin, 2006) due to the increase in atmospheric humidity, similar to the rest of the planet.

Potential impact on evapotranspiration

Evapotranspiration[3] is one of the fundamental components in the hydrological cycle and must be studied in any effort to assess the consequences of an increase in temperature on the hydrological balance of a region or river basin. However, the importance of this variable contrasts with the fact that there are very few direct measurements of effective evapotranspiration[4] for all land masses (Boé, 2007), in spite of a few initiatives such as the Fluxnet[5] network. Variations in evapotranspiration are caused not only by the level of humidity, but also by the available energy, surface winds and CO_2 concentrations (i.e. their impact on plant transpiration). Generally speaking, greater evapotranspiration may be expected in regions where water stress does not increase (e.g. tropical forests and zones where precipitation increases).

Observed impact on runoff and extreme situations

Even though a vast number of studies have been carried out on the impact of climate change on river discharges, no clear trends on the planetary scale have been noted (Bates, 2008). This is due primarily to the fact that it is very difficult to distinguish between the effects of climate change and those caused by human activities (changes in land use, creation of reservoirs, etc.). In addition, the sparse spatial distribution of data-collection points makes it particularly difficult to obtain a clear signal. This is true for France as well. Analysis of over 200 data series on daily discharges did not reveal any general changes over the past century (Grésillon *et al.*, 2007). In a limited number of cases, significant downward trends in the interannual mean discharge of rivers not influenced by anthropogenic factors (see Box 1) have been noted over the past 40 years in the southern section of France and more precisely in the Pyrenees and the Cévennes (Giuntoli, 2012). It is however difficult to establish a causal link with climate change due to the Atlantic multidecadal oscillation (see footnote n° 2) (Boé and Habets, 2014).

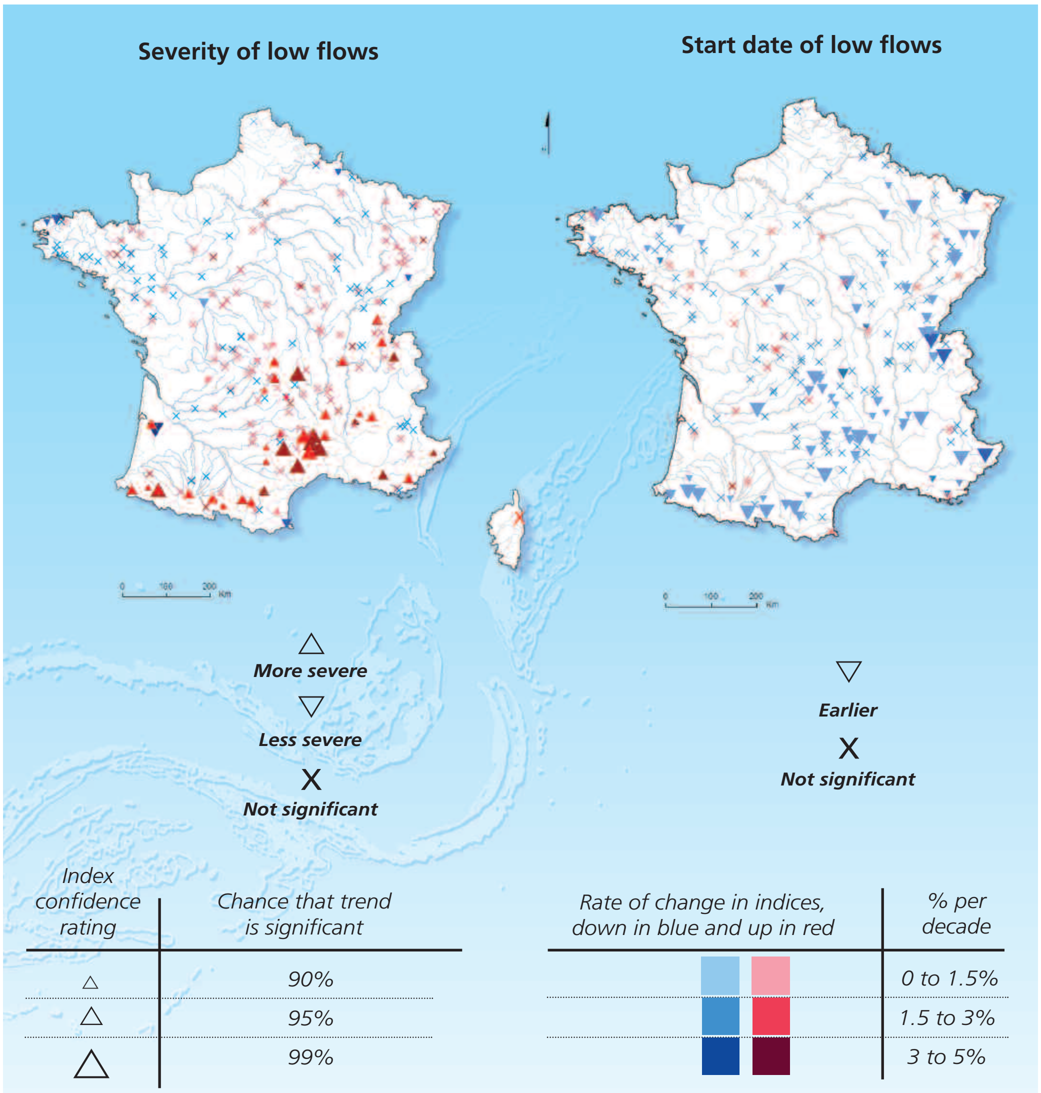
Similarly, most studies conclude that no significant and general trends are detectable in flood volumes since the middle of the last century (Renard *et al.*, 2006; Renard, 2006). This lack of a clear trend is due to high regional variability. That being said, more frequent extreme flooding has been noted in the Alps over the past 20 years due to increases in the discharges of rivers supplied by glaciers (Bard *et al.*, 2012). Also, in some places, earlier peak spring flooding has been noted due to earlier melting of snow packs (OsCC, 2011).

3. Quantity of water entering the atmosphere due to evaporation from the soil and transpiration by plants.
4. For this reason, one does not speak of observed impact, but of the potential impact of climate change on this variable.
5. http://fluxnet.ornl.gov/introduction

Concerning low-flow levels, no significant changes have been observed in the northern section of France or in nival rivers (Giuntoli and Renard, 2010; Giuntoli *et al.*, 2012). Of interest, however, is a study on two nival rivers, the Chéran and Isère Rivers, which noted a reduction of over 35% in their discharges at the beginning of the summer season (OsCC, 2011). It would also appear that the low-flow period occurred earlier during the summer, however no trend has yet been confirmed (see Figure 9).

Finally, in the southern section of France, the severity and duration of low-flow periods would appear to have increased from 1968 to 2007, though it is difficult to determine the origin of this phenomenon (measurement problems, cyclical variations in atmospheric and ocean currents in the Atlantic, global warming due to the increase in GHGs).

Figure 9



Trends detected over the period from 1968 to 2007 concerning the severity (on left) and the timing (on right) of low-flow periods, on the basis of 236 hydrometric monitoring points in continental France. The low-flow period occurred earlier in the year at 32% of the monitoring points (diagrams modified, originally from Giuntoli and Renard, 2010; Giuntoli et al., *2012).*

Box 1

Common hydrological variables

The discharge of a river is the volume of water flowing through the cross-sectional area of the river per unit of time. Discharge is expressed in cubic metres per second (m^3/s). The following discharges are commonly used.

- Daily mean discharge. Ratio between the volume of the flow for a full day (0-24 hours) and the corresponding duration. The volume is calculated using the record of instantaneous discharges.
- Monthly, annual and interannual mean discharge. Mean value, for the given period, of the daily mean discharges. The interannual mean discharge is the mean value of the annual mean discharges.
- Natural discharge. Discharge that would occur in the absence of a hydraulic structure modifying the river regime at the monitoring point. Values are calculated only for monthly and annual discharges.
- Influenced discharge. Discharge of a river disturbed by human activities, but such that flows retain their general characteristics.
- Annual minimum monthly discharge with a five-year return period (QMNA5). Monthly discharge that has an 80% chance of being exceeded each year. This variable is used to characterise a calender month with low hydraulic conditions.
- Low-flow discharge. Minimum discharge in a river calculated over a given time period when water levels are at their lowest in the year. For a given year, one may speak of the daily low-flow discharge, the low-flow discharge over x consecutive days or the minimum monthly discharge (the average of the daily discharges during the month of least discharge).

Low-flow discharges may also be expressed as averages over several consecutive days. For example, the period may be the month with the least discharge (QMNA, annual minimum monthly discharge), the three days with the least discharge (VCN3, minimum mean discharge over three consecutive days) or any number of days (VCNx). Similarly, the floods during a year may be characterised using the maximum instantaneous discharge (QIX) or the maximum daily discharge (QJX).

Finally, the return period of floods and low-flows is commonly mentioned. This term characterises the frequency of the phenomena and corresponds to the reciprocal of the probability that the event in question will occur or be exceeded each year. For example, a flood with an annual frequency of 0.1 has a ten-year return period and one speaks of a "ten-year flood". Such a flood has a 10% chance of occurring or being exceeded each year.
Source: www.hydro.eaufrance.fr/glossaire.php

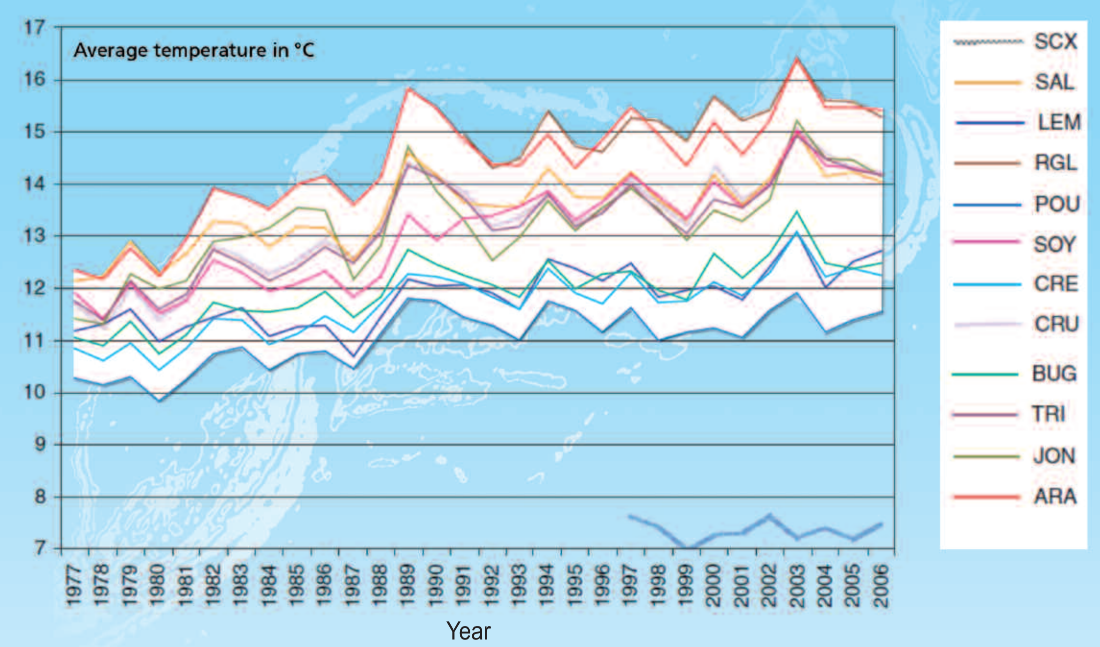
Observed impact on groundwater

Groundwater levels depend heavily on the distribution of precipitation between evapotranspiration, surface flows and infiltration to groundwater. It follows that climate change will necessarily have an impact on groundwater reserves. However, to date, no general trends, either temporal or spatial, have been detected in continental France. The results by Vernoux and Seguin (2011) indicate that the available data series are too short, the spatial distribution of monitoring points is too heterogeneous and there are too many confounding factors, notably human activities and the Atlantic multidecadal oscillation.

Observed impact on water temperatures

Over the last decades, the increase in air temperatures has gone hand in hand with a rise in water temperatures in rivers and lakes. Poirel (2008) notes for example a general upward trend in the Rhône River and its tributaries between 1977 and 2006. The increase is almost 1°C in the Saône, it rises to 1.5°C in the Ain and in the Rhône downstream of the Bugey and even 2°C downstream of the Isère (see Figure 10).

Figure 10



Monitoring points
SCX = upstream of Lake Geneva
LEM = downstream of Lake Geneva
POU = 25 km downstream of Lake Geneva
CRE = upstream of Creys-Malville power plant
BUG = upstream of Bugey power plant
JON = downstream of Ain/Rhône confluence
SAL = upstream of Saint Alban power plant
RGL = upstream of Isère/Rhône confluence
SOY = downstream of Isère/Rhône confluence
CRU = downstream of Drôme/Rhône confluence, upstream of Cruas-Meysse power plant
TRI = upstream of Tricastin power plant
ARA = downstream of Durance/Rhône confluence

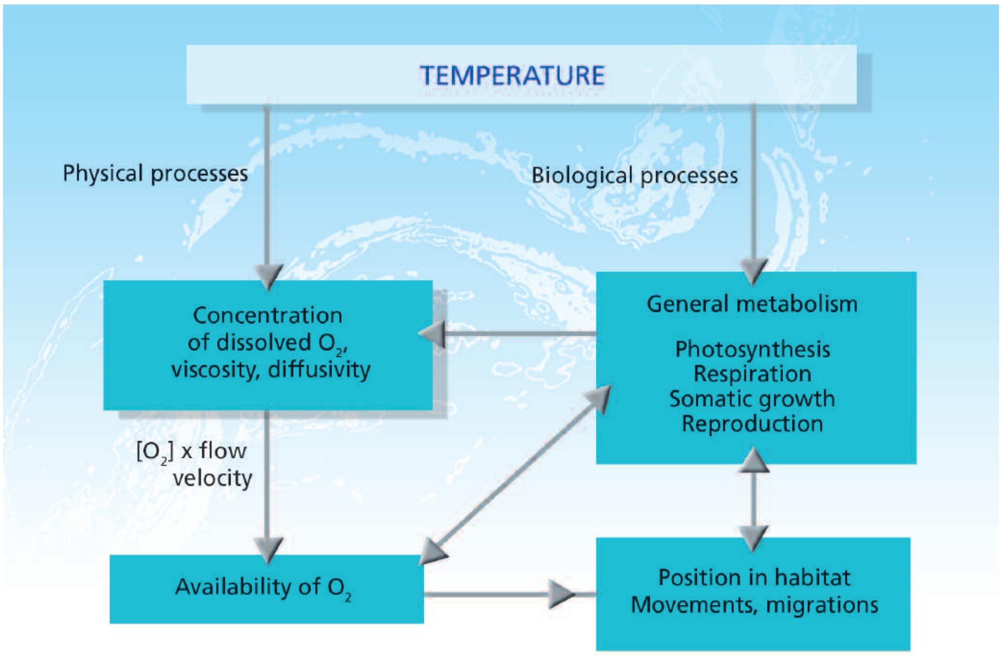
Averaged annual water temperatures along the Rhône River (Poirel et al.*, 2008).*

Similar to the Rhône, study of temporal data series for the mid-Loire River revealed an average annual temperature rise of 1.2°C between the first and last decade of the 32-year period from 1977 to 2008. The primary reason is a rise in air temperatures and the second is a decrease in discharges (Floury, 2012). These results are in line with previous observations by Moatar and Gailhard (2006) on the Loire from 1976 to 2003, as well as with data from other major European rivers, e.g. an increase of 1.4 to 1.7°C over the last century for the Danube and its tributaries (Webb and Nobilis, 2007). The same trends have been noted for lakes. Measurements carried in Lake Bourget, at a depth of two metres over the period from 1984 to 2011, signal an average increase of 1.1°C, with the highest values noted in 2003 and 2011 (OsCC, 2012). However, caution is advised when interpreting these results because the time span of the data series underlying the analysis is generally less than 40 years. In addition, other factors explaining the phenomena must be taken into account, for example human activities and cyclical variations in atmospheric and ocean currents in the Atlantic, notably the Atlantic multidecadal oscillation (Sutton and Hodson, 2005; Sutton and Dong, 2012; Boé and Habets, 2014).

Potential impact on water chemistry

Water temperatures directly and indirectly impact many chemical (concentration of dissolved oxygen, viscosity, diffusivity) and biological functions (plant and animal metabolisms) (see Figure 11). An increase in temperature could modify the balance between oxygen availability and metabolic needs (Dumont *et al.*, 2007), thus increasing the risks of trophic imbalances (Fabre, 2012). However, no studies on the subject are currently available.

Figure 11



Links between temperature and oxygen availability, and the impacts on aquatic ecosystems (according to Dumont et al.*, 2007). Note that the maximum concentration of dissolved oxygen in water decreases as the temperature rises. For example, at 10°C, the maximum concentration of dissolved oxygen is 11 mg/L, but at 30°C, the maximum concentration is only 7 mg/L.*

Conclusion

The observed changes in climate and hydrology are in line with the expected consequences of the increase in GHGs emitted by human activities over the past two centuries (IPCC, 2007; Cook *et al.*, 2013). The trend data for air temperatures are fairly clear and consistent worldwide, however it is more difficult to detect a trend in the qualitative and quantitative changes in water resources over the past century. In addition, when trends are observed, it is often difficult to establish a causal link with climate disruptions due to the existence of many confounding factors (human activities, the Atlantic multidecadal oscillation, etc.).

The next section is a presentation of the models used to project changes in water resources in view of assessing the possible consequences of climate change. The uncertainties inherent in these models are also noted.

Modelling tools to project changes in the climate and in water resources

Digital models are required to assess the degree of climate change, anticipate the impacts and take adaptive measures. Such models, based on equations governing fluid mechanics and energy conservation, were first developed in the United States starting in 1960 and became increasingly complex in order to produce more precise and robust projections of the future climate.

Climate change is a function of GHG emissions, which explains why GHG-emissions scenarios were proposed by the IPCC and are used by climatologists as input data for climate models. The climate scenarios produced by the models are in turn used in impact models that simulate the effects of climate on hydrology and ecosystems.

Emissions scenarios for greenhouse gasses

Scenarios on the future composition of the atmosphere, also called SRES (Special Report on Emissions Scenarios) scenarios, were devised on the basis of socio-economic projections (demographics, life styles, new technologies, etc.) (Nakićenović and Swart, 2000). Four basic scenarios were formulated (see Figure 12).

- **Scenario A1.** Convergence between North and South, economic development similar to the current situation. This scenario is divided into three groups describing different energy strategies. A1FI corresponds to intensive use of fossil fuels, A1T calls on non-fossil energy resources and A1B corresponds to a balance across all sources.
- **Scenario B1.** Convergence between North and South, economic development taking environmental concerns and sustainability into account.
- **Scenario A2.** Heterogeneous situation, economic development similar to the current situation. This scenario most closely corresponds to the present situation.
- **Scenario B2.** Heterogeneous situation, economic development taking environmental concerns and sustainability into account.

As mentioned above, the GHG concentrations estimated using these scenarios served until recently as input data for models simulating the future climate.

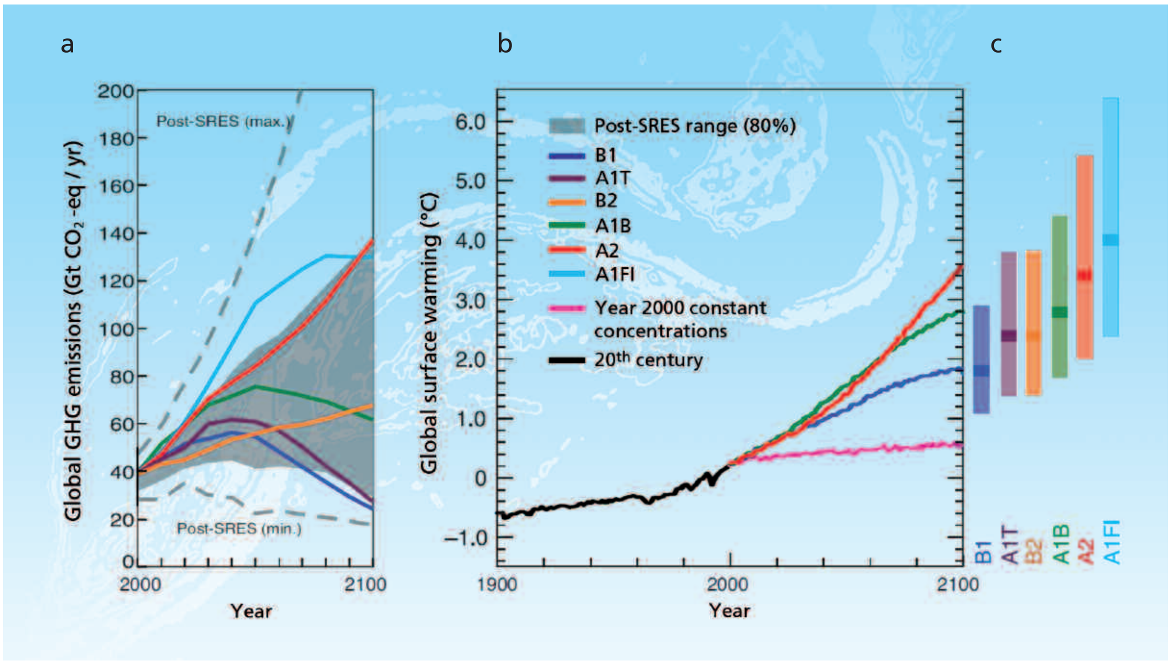
Starting with the preparation of the Fifth IPCC assessment report, parts of which started to be published in 2013, a different approach was adopted in order to encourage the emergence of adaptation scenarios. This time, to assess the evolution of the climate in the future, the IPCC experts defined *ex anti* four trajectories for GHG emissions and concentrations, called Representative Concentration Pathways (RCP) (Moss *et al.*, 2008, 2010). The RCPs are used by the various teams of experts (climatologists, hydrologists, agronomists, economists, etc.)

that all worked in parallel for the first time. On the basis of the RCPs, climatologists produce global and regional climate projections. Economists devise scenarios, called Shared Socio-Economic Pathways (SSP), used to define worldwide socio-economic conditions that are compatible with the various RCPs.

Four families of RCPs have been developed.

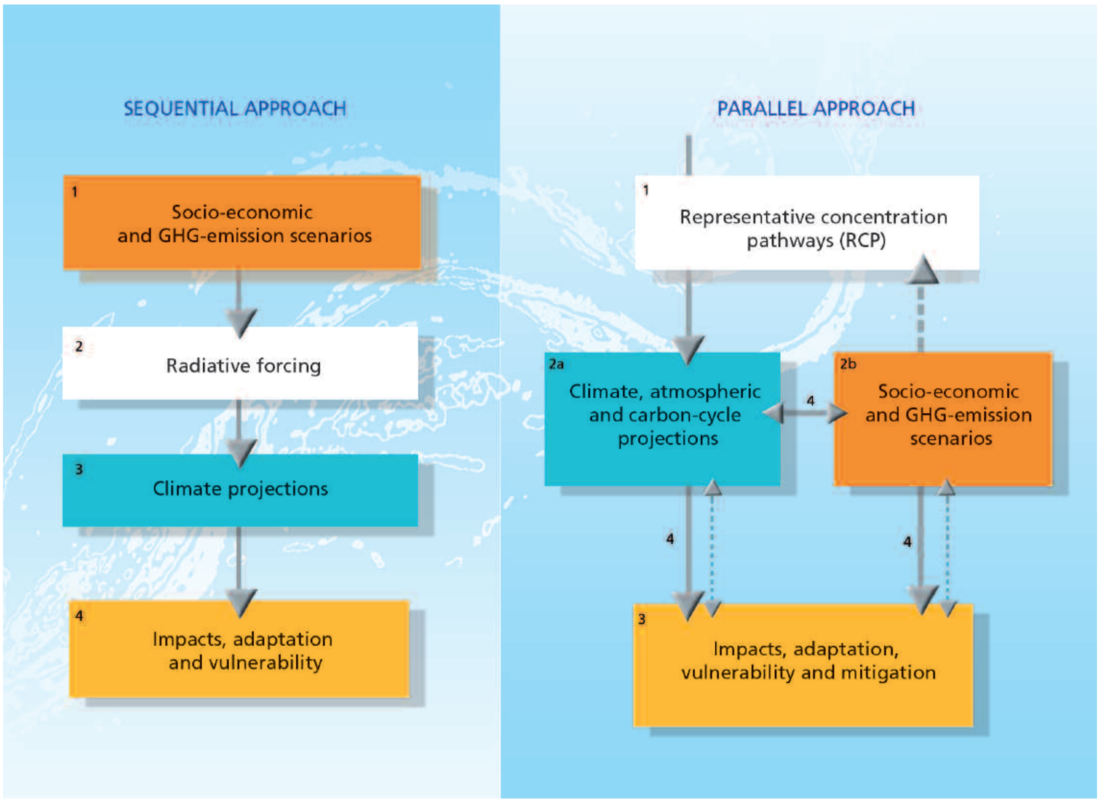
- **RCP 8.5.** In the year 2100, radiative forcing reaches 8.5 W/m², which corresponds to a CO_2-equivalent concentration of approximately 1 370 parts per million by volume (ppmv). Radiative forcing continues to increase strongly in 2100.
- **RCP 6.** In the year 2100, radiative forcing reaches 6 W/m², which corresponds to a CO_2-equivalent concentration of approximately 850 ppmv. Radiative forcing stabilises after 2100.
- **RCP 4.5.** In the year 2100, radiative forcing reaches 4.5 W/m², which corresponds to a CO_2-equivalent concentration of approximately 650 ppmv. Radiative forcing stabilises after 2100, but stabilisation begins around 2060.
- **RCP 2.6.** Radiative forcing reaches a peak of 3 W/m² (CO_2-equivalent concentration of approximately 490 ppmv) before 2100 and decreases subsequently. In the year 2100, it is approximately 2.6 W/m². This scenario is also called RCP 3-PD, i.e. 3 W/m² and peak decline. It is the only scenario in which the rise in global temperatures remains below 2°C.

Figure 12



Scenarios for GHG emissions from 2000 to 2100 and projections of surface temperatures.
a. Global GHG emissions in the absence of climate policies. Six illustrative SRES marker scenarios (coloured lines) and the 80th percentile range of recent scenarios published since SRES (post-SRES) (grey shaded area). Dashed lines show the full range of post-SRES scenarios.
b. Solid lines are multi-model global averages of surface warming for scenarios A2, A1B and B1, shown as continuations of the 20th-century simulations. The pink line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values.
c. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099.
All temperatures are relative to the period 1980-1999 (IPCC, 2007).

Figure 13



Presentation of the sequential (SRES) and parallel (RCP and SSP) approaches. The numbers correspond to the different steps, where steps 2a and 2b are carried out simultaneously. The solid arrows signal information transfers, the thick dotted arrow corresponds to RCP selection and the thin dotted arrows indicate information integration for the assessment of impacts and the formulation of mitigation and adaptation strategies (diagrams modified, originally from Moss et al.*, 2008).*

The correspondence between RCPs and SRES scenarios is not always obvious because a given RCP may be compatible with several SRES scenarios. That is the case for RCP 4.5 which may be compatible with three of the SRES scenarios (A2, B1 and B2). Conversely, a given set of SRES scenarios may be compatible with several RCPs.

General circulation models

All the compartments of the climate system and their interactions must be taken into account in climate models. The digital models currently used, called Global Circulation Models (GCM), are in fact sets of interlinked modules (atmosphere, oceans, sea ice, etc.). The complexity and quantity of the necessary calculations require enormous computer resources and budgets. For these reasons, the horizontal resolutions of global models are, for the time being, fairly low (grid size of approximately 200 km for the finest resolutions).

Such low resolutions may have a major impact on simulations, notably for precipitations that are generally highly dependent on the local context. France is a good example of this problem. Given its complex topography, climate regimes can vary significantly over short distances. For this reason and to improve modelling results, regionalisation methods have been developed.

Regionalisation of climate scenarios

There are several ways to enhance the spatial-temporal resolution and correct the biases (poor representation of relief, poor integration of marine influences, physical errors) of climate models. These methods, called downscaling, regionalisation and spatial disaggregation, can be used to reveal detailed information on local conditions that are consistent with the observed values.

There are two main approaches to increasing the spatial-temporal resolution of climate models.

■ Dynamic downscaling, i.e. improving the resolution of the global models. There are three families of models:

- high-resolution global models covering the entire planet that require long calculation times and large budgets;
- variable-resolution global models start with a uniform grid covering the entire planet, but the grid can be modified to achieve higher spatial resolution for the studied zone. The ARPEGE-Climat (Météo-France) and LMDZ (IPSL LMD) models are of this type (Gibelin and Déqué, 2003) and are capable of zooming in to resolutions of a few dozen kilometres;
- regional models covering only a part of the planet (e.g. Europe) and having data ranges limited by global models with lower resolutions. This method can be used to achieve high spatial resolutions (10 to 20 km) required to realistically simulate the local climate (relief, land-sea contrast, complex coast lines) and to take into account regional physical processes.

■ Statistical downscaling, based on defining a statistical relation between low-resolution global variables and high-resolution local surface variables. There are numerous statistical methods to project global variables to the local level and each has application limits specific to its internal structure.

Note that statistical corrections are often required to avoid significant distortion of the results, whatever the type of downscaling employed.

Hydrological models

Following climate modelling, the resulting projections are fed into hydrological models to assess their impact on different local hydrological variables (interannual mean discharge, flood discharge, low-flow discharge, etc.). There are two main types of models:

■ the first type attempts to reproduce the observed physical processes, for example in a river basin. They are called mechanistic (or explicit) models, one example being the SAFRAN-ISBA-MODCOU models coupled as SIM[6] (Habets *et al.*, 2008);

■ other models are said to be conceptual, e.g. the GR4J and GARDENIA models (Perrin *et al.*, 2003; Thiéry, 2003). They attempt to precisely reproduce the observations, but without taking into account all the physical processes.

Conceptual models often produce excellent results over the period covered by the data, but they are theoretically not designed to react well outside of the situation for which they are calibrated, e.g. for a change in land cover. Conversely, physical models require good characterisation of the environment, e.g. soil and vegetation. This data is generally difficult to acquire and these models often do not offer the same level of performance as conceptual models over recent time periods. However, they are thought to be more robust in situations where the climate and environmental conditions are modified.

6. The Safran-Isba-Modcou coupled model was developed in a partnership between CNRM-GAME and the Geosciences centre at Mines ParisTech.

Uncertainty at every step

Considerable uncertainty accompanies climate and hydrological projections and must be taken into account in studies attempting to predict the impact of climate change on human populations and the environment (see Figure 14).

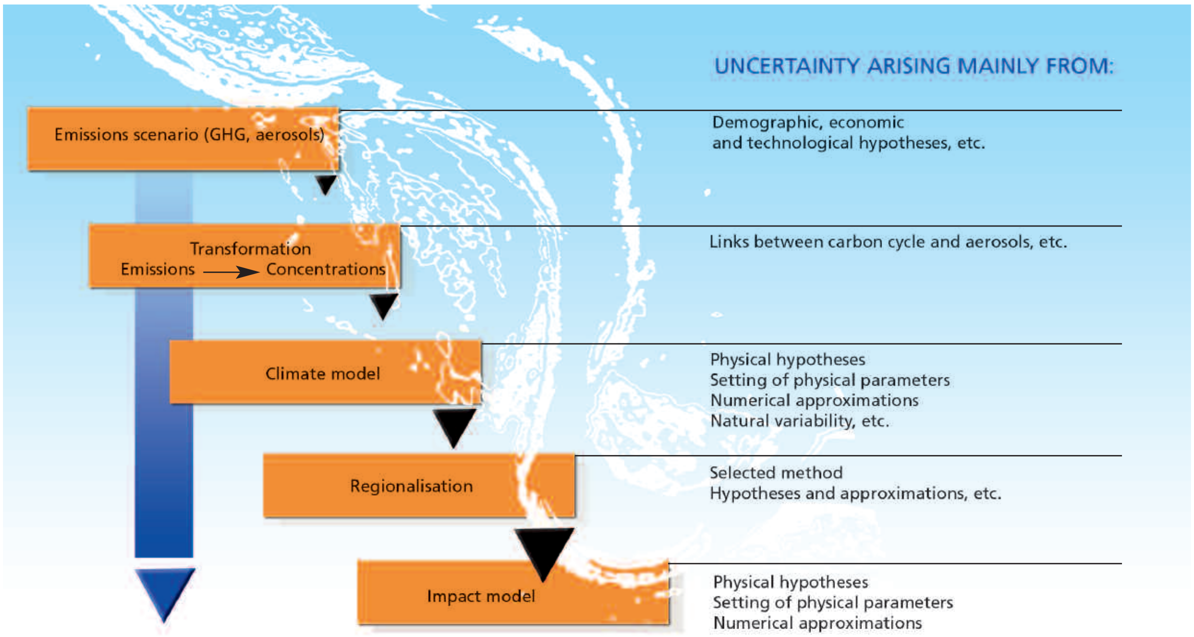
Concerning GHG emissions scenarios, the uncertainty is due to the hypotheses selected as well as to changes in society.

Concerning the models themselves, their design and the resolution methods employed raise a number of questions. These questions are amplified by downscaling, the complexity of the phenomena involved, the interactions between variables and feedback loops.

The translation of the projections resulting from the climate models into hydrological terms, particularly concerning extreme conditions, is also a source of significant uncertainty. This is because current models are primarily based on the stationarity hypothesis[7] which, in the field of climate change, is widely debated.

In addition, hydrological models still do not take into account certain variables (Fabre, 2012). For example, the influence of vegetation is not explicitly integrated in conceptual models (land cover). Similarly, human factors, such as abstractions and dams, are rarely taken into account, which limits the capacity to clearly distinguish between the effects of climate change and anthropogenic pressures.

Figure 14



Cascading uncertainty when carrying out a study on climate change (according to Boé, 2007).

7. Average climate values and their variability are considered constant. But the climate is obviously not stationary. It has evolved greatly since the beginning of the Earth and will continue to do so in the future.

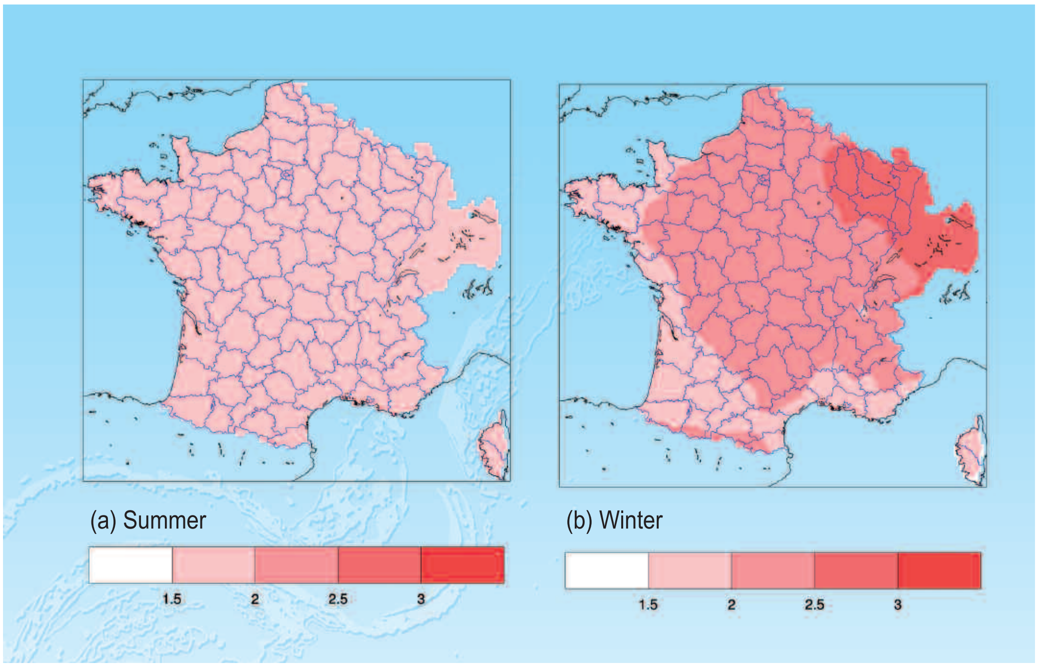
The future climate and water resources in continental France

Over the past few years, the scientific community has worked intensively on the issues of climate change and its effects on society. The models described above made possible multi-disciplinary projects that quantified the expected impacts on water resources. This section presents the results for France concerning a certain number of climate and hydrological variables (all the results presented here are drawn from the studies based on CMIP3 / IPCC AR4).

Projected impact on air temperatures

For France as a whole, all the scenarios project an increase in air temperatures ranging from 1.5 to 3°C by 2050. The results of simulations up to the year 2100 are less clear and project an increase of approximately 2 to 4.5°C compared to current temperatures (Déqué *et al.*, 2005) (see Figure 15). Extreme events such as heat waves in the summer should also be more frequent (Déqué, 2007).

Figure 15

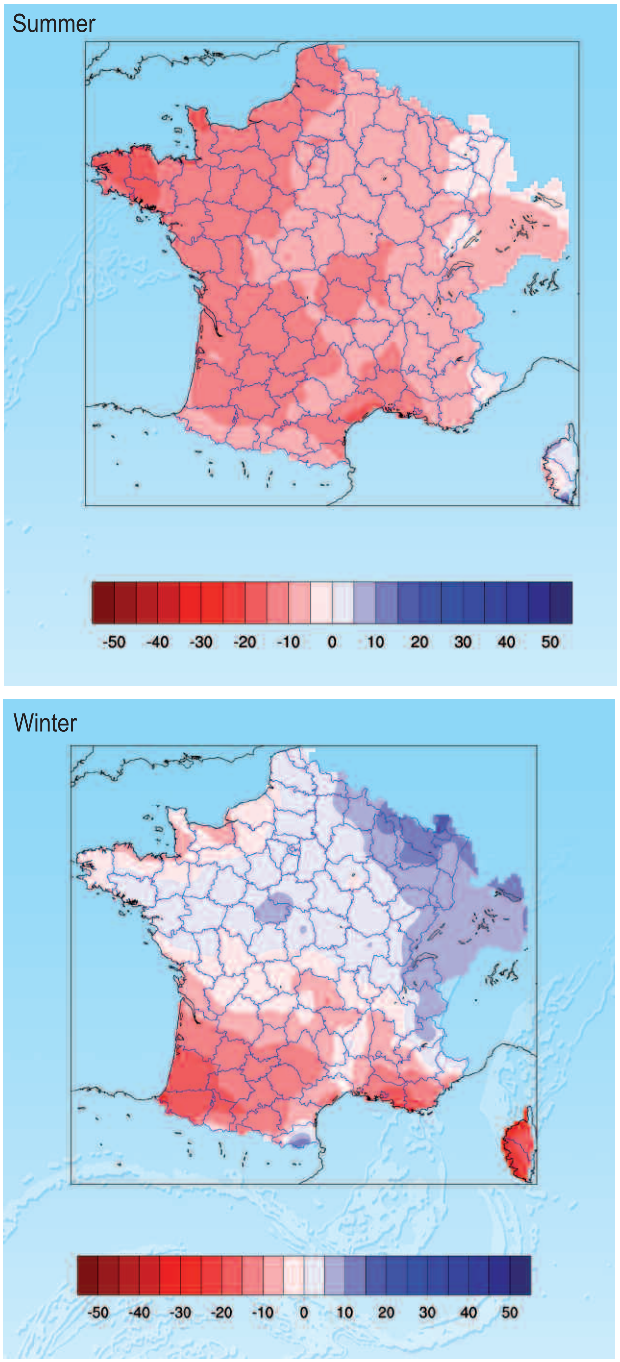


Multi-model averages of temperature anomalies (in °C) during (a) the summer period (June, July, August) and (b) the winter period (December, January, February), for the years 2046 to 2065, compared to the 1961-1990 averaged value. Results drawn from 15 IPCC and 7 ARPEGE V4 simulations (Pagé and Terray, 2011).

Projected impact on precipitation

Regionalised projections based on scenario A1B used in 15 IPCC and 7 ARPEGE simulations (Météo-France model) comparing the periods 2046-2065 and 1961-1990 indicate that summer precipitations will decrease in virtually every part of the country (Boé, 2007; Pagé and Terray, 2011; see Figure 16). For the winter, the simulations project an increase, notably in the Centre region and the north-eastern section of the country, but a decrease in the south-western section (Boé, 2007). Any change would be limited in the spring (Drias; Météo-France data; CERFACS; IPSL, 2013). Finally, the simulations do not detect any clear trends for the fall (Drias; Météo-France data; CERFACS; IPSL, 2013).

Figure 16



Multi-model averages of precipitation anomalies (in mm/year) during the summer period (June, July, August) and the winter period (December, January, February), for the years 2046 to 2065, compared to the 1961-1990 averaged value. Results drawn from 15 IPCC and 7 ARPEGE V4 simulations (Pagé and Terray, 2011).

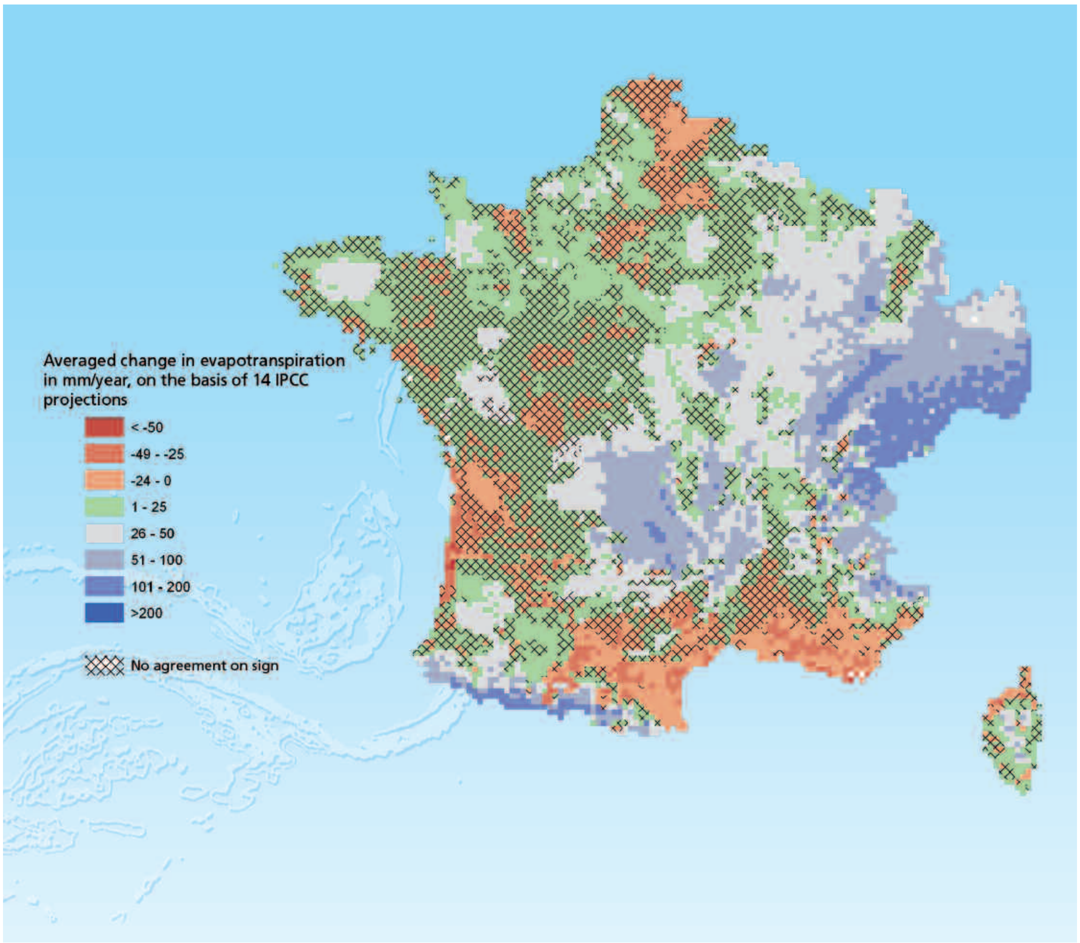
Concerning extreme events, the projections made for Europe using high-resolution global models indicate an increase in heavy rainfall during the winter and, conversely, an increase in the duration of dry periods during the summer (Déqué, 2007).

Finally, concerning snowfall, all the models focussing on the Alps and the Pyrenees predict a major reduction in snowfall at lower altitudes and a less significant reduction at higher altitudes (Beniston, 2005; Lopez-Moreno *et al.*, 2009).

Projected impact on evapotranspiration

Boé (2010) ran a study on France specifically to quantify the possible variations in effective evapotranspiration. The simulations, using a physical model (SIM) and 14 disaggregated climate projections according to scenario A1B, signal a sharp reduction in evapotranspiration on the Mediterranean and Atlantic coasts, but an increase in the eastern section of the country and at higher altitudes (see Figure 17). Note that depending on the climate and hydrological models used, the projected changes in effective evapotranspiration are particularly heterogeneous (Habets *et al.*, 2013).

Figure 17

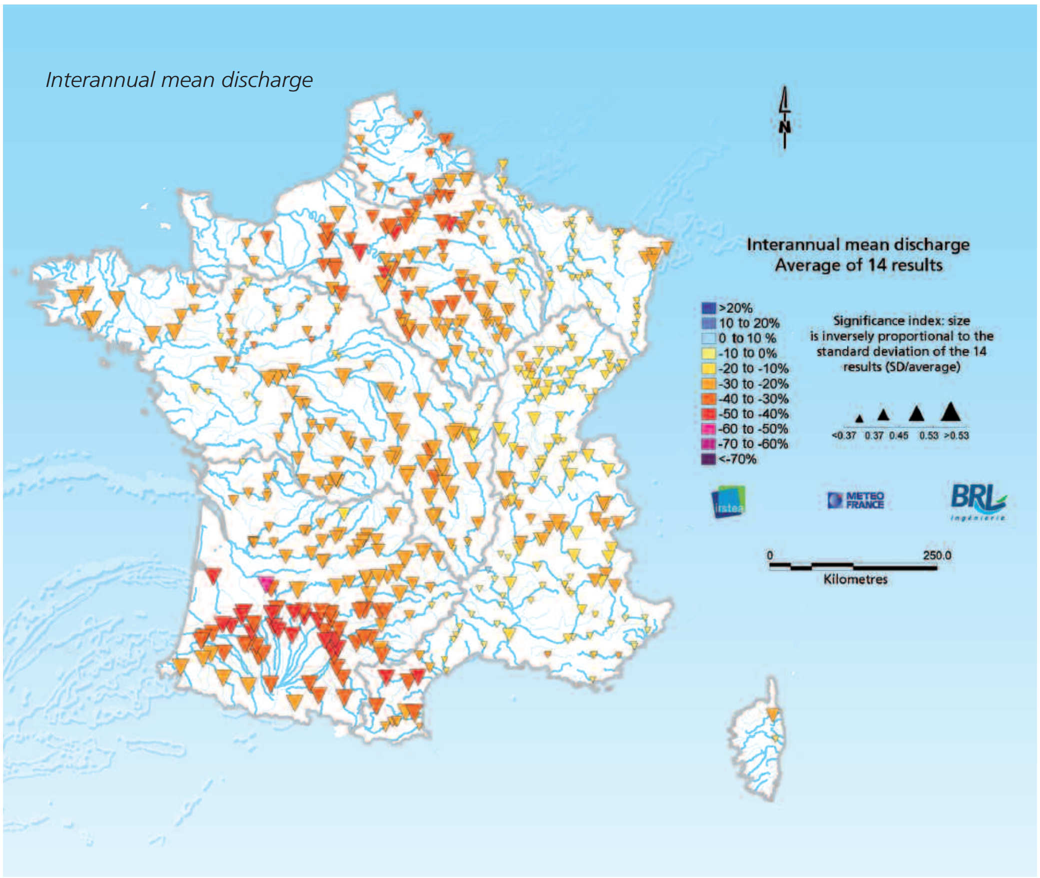


Change in effective evapotranspiration in 2050 calculated by the SIM model, on the basis of 14 regionalised climate projections according to scenario A1B, in millimetres per year (Boé et al.*, 2009). Cross-hatching indicates regions where there is significant uncertainty among the projections concerning the sign of change (plus or minus).*

Projected impact on runoff and extreme situations

Climate change will have a strong impact on runoff and river discharges. The results of the Explore 2070 project, using seven climate projections (scenario A1B, for the period 2046-2065) and two hydrological models (GR4J and SIM), signal a probable drop in the interannual mean discharge throughout continental France, of approximately 10 to 40% in a majority of river basins (Chauveau *et al.*, 2013; see Figure 18). The foothills of the Pyrenees will be particularly affected with drops ranging from 10 to 60%. The main cause is a drop in the cumulative annual precipitation coupled with an increase in evaporative demand.

Figure 18

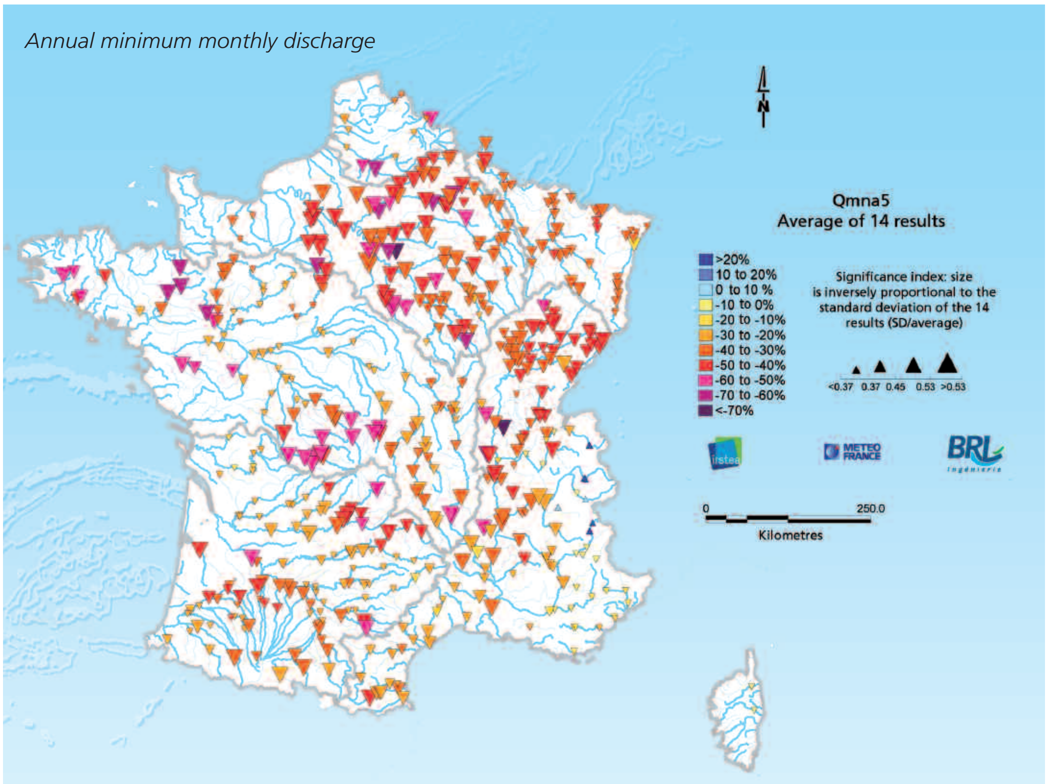


Possible changes in the interannual mean discharge (%) in the period 2046-2065, compared to the 1961-1990 value (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013; Chauveau et al.*, 2013). The results are the averaged outputs of two hydrological models (GR4J and SIM) that were supplied with the disaggregated outputs of seven climate models (a total of 14 simulations according to scenario A1B).*

Concerning low-flow discharges, a majority of the simulations agree that there will be a general drop even greater than that for the interannual mean discharge. The annual minimum monthly discharge with a five-year return period (QMNA5, see Box 1) could decrease by 5 to 65%, depending on the region (see Figure 19).

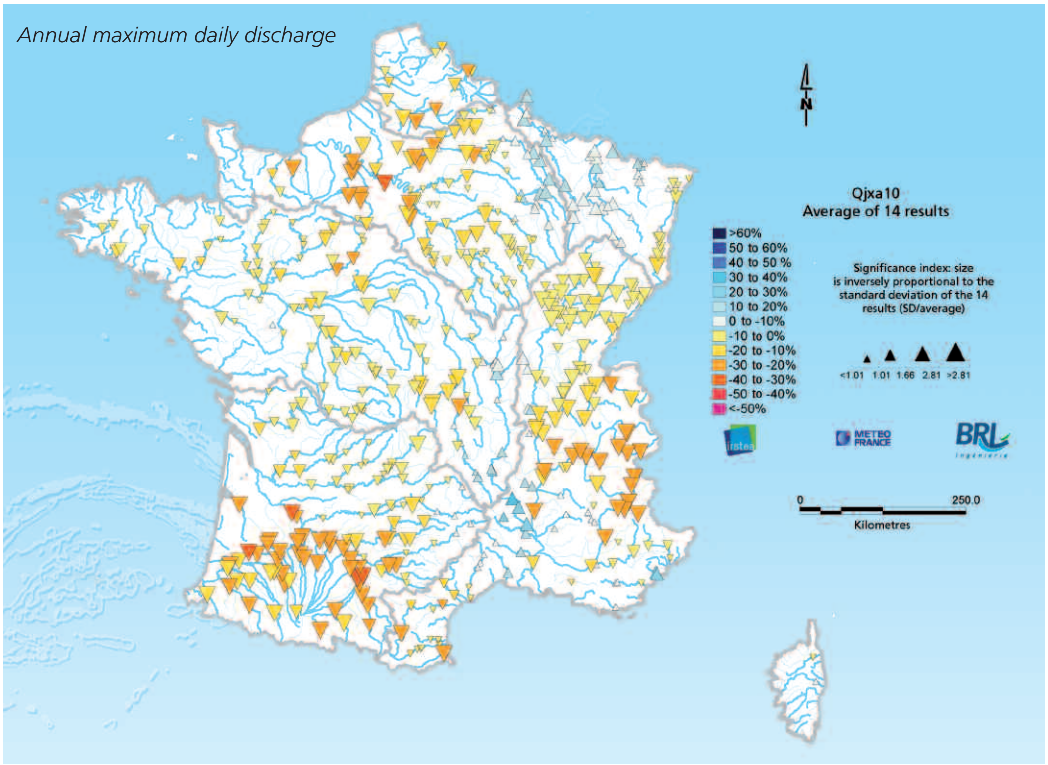
The discharges for the months of August and September in river basins with a pluvial oceanic regime could drop by 30 to 70% over large parts of the country. This reduction in discharges could be particularly severe in the Seine-Normandie basin, on the left bank of the Garonne River and in the northern half of the Rhône-Méditerranée basin. Concerning flood risks, the annual maximum daily discharge with a ten-year return period (QJXA10) could increase in the Cévennes and in the north-eastern section of the country (see Figure 20).

Figure 19



Possible changes in the annual minimum monthly discharge with a five-year return period (QMNA5 in %) in the period 2046-2065, compared to the 1961-1990 value (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013; Chauveau et al.*, 2013). The results are the averaged outputs of two hydrological models (GR4J and SIM) that were supplied with the disaggregated outputs of seven climate models (a total of 14 simulations according to scenario A1B).*

Figure 20



Possible changes in the annual maximum daily discharge with a ten-year return period (QJXA10 in %) in the period 2046-2065, compared to the 1961-1990 value (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013; Chauveau et al.*, 2013). The results are the averaged outputs of two hydrological models (GR4J and SIM) that were supplied with the disaggregated outputs of seven climate models (a total of 14 simulations according to scenario A1B).*

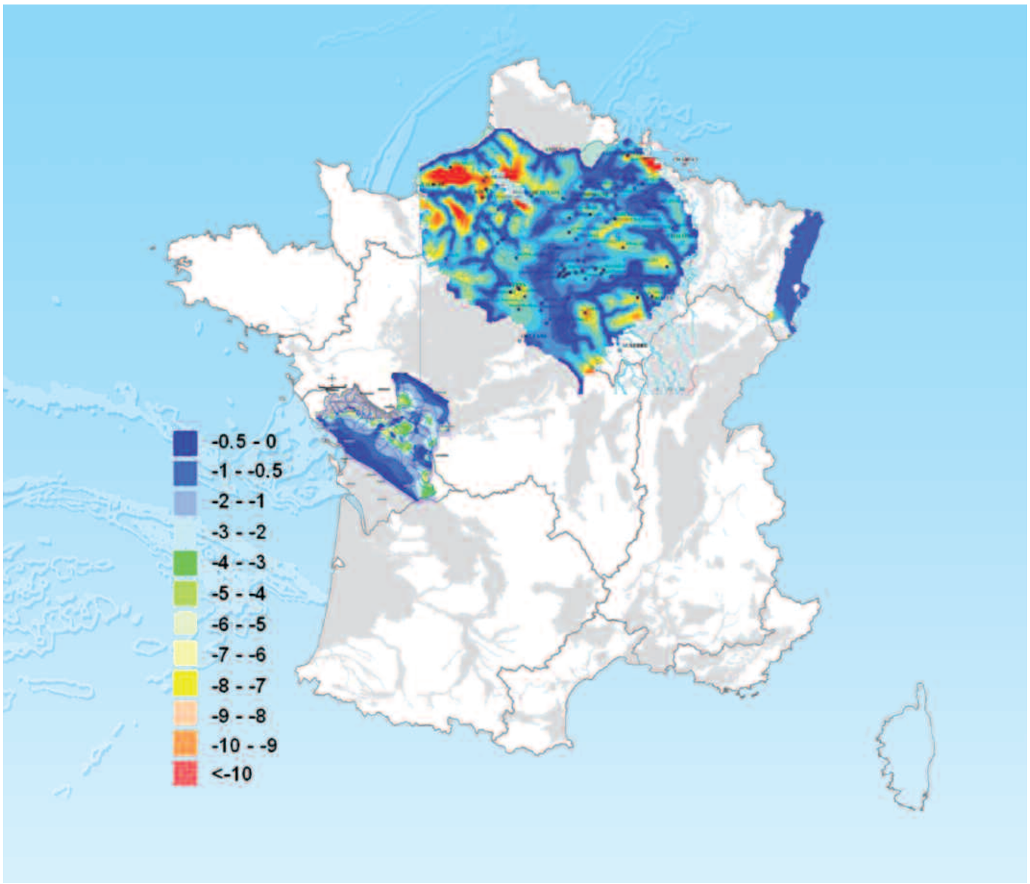
Projected impact on groundwater

A number of studies project a major change in the recharge and the piezometric levels of large groundwater bodies. In France, a more or less general decrease in groundwater recharge of 10 to 25% is expected (Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013; Boé *et al.*, 2009). The south-western section of the country could be the most severely impacted with reductions of 30 to 50% (Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013; Boé *et al.*, 2009).

Concerning piezometric levels, the simulations all signal a drop in monthly mean levels due to the decrease in recharge. Spatially speaking, the results vary widely depending on where the piezometers are located, with slighter variations in valleys compared to plateaus situated farther from a river. Among the more optimistic projections, very slight drops of approximately 0.5 to 1.5 m are foreseen, e.g. throughout most of the Seine and Rhine River basins, and even local increases in some regions, e.g. Poitou, confined groundwater in the Aquitaine region (Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013; Habets *et al.*, 2013; see Figure 21). The more pessimistic projections suggest major reductions of up to ten metres on plateaus, e.g. the Caux and Beauce areas, and significant but more limited drops of 1 to 4 m in basement aquifers.

These severe drops may be explained primarily by a reduction in rainfall and a considerable increase in evapotranspiration, the latter due to the increase in temperatures insufficiently compensated by an increase in the humidity of the air.

Figure 21



Change in piezometric levels (in m) in three river basins for the period 2046-2065, if there is no change in the pumped volumes. ARPEGE projection, scenario A1B, Explore 2070 - MEDDE/MINES ParisTech/BRGM, 2013.

Projected impact on water temperatures

The trend in water temperatures will be similar. Modelling work for the Explore 2070 project estimated on the basis of 31 monitoring points throughout the country that the average annual increase in water temperatures would be 1.6°C (Explore 2070 - MEDDE/Météo-France; Irstea; BRLi, 2013). This increase could, however, vary from a minimum of 1.1°C to a maximum of 2.2°C. These average increases mask major differences between monitoring points, with median increases in water temperatures between 0.6 and 2.2°C, and between 2 and 2.5°C for air temperatures.

Interactions between climate change and anthropogenic pressures

The data presented above highlights the severity of the changes expected in the decades to come. The impact of these changes on the water cycle could be heightened or attenuated by human activities. For example, channelling or impoundment of rivers could worsen the floods that will probably be more frequent in the decades to come. Changes in land use, notably agricultural practices, could increase the risks of erosion and excess suspended matter at the heads of river basins, given the probable increases in extreme events (heavy rains). Urban sprawl could limit infiltration surfaces, thereby worsening peak flood levels and reducing groundwater recharge. Increased irrigation, the development of crops requiring large amounts of water during low-flow periods (fuel crops, corn, poplar trees, etc.) or population growth in certain regions of France could all contribute to increased abstractions, with as a result reductions in average discharges in rivers and in groundwater piezometric levels, and greater risks of severe low-flow discharges during the summer.

Finally, degraded water quality in conjunction with an increase in the temperature could cause modifications in the fate and the distribution of chemical substances between the various environmental compartments, which would in turn modify the conditions for aquatic organisms in terms of exposure, bioavailability and consequently the toxicity of the substances (Stahl *et al.*, 2013 ; see Box 2).

Box 2

Impact of climate change on water quality

A great diversity of pollutants exist in water and aquatic environments. They come from many sources (industry, agriculture, towns) are are present as mixtures at low concentrations, but can provoke malfunctions in aquatic ecosystems (Schwarzenbach *et al.*, 2006; see Table 1). In the absence of drastic measures to reduce GHG emissions, it must be presumed that climate change will affect water quality in the decades to come. The effects may manifest themselves in different ways (EEA, 2011).

The increased severity and frequency of dry periods will result in major modifications to the hydrological regimes of rivers, which will lead in turn to reduced capacity to dilute contaminants. These effects may, however, be attenuated by increased residence times for contaminants in water, which would contribute to their degradation. In regions where precipitation will increase, the quantity of pollutants released to the environment via urban wastewater following rainfalls will be increased, as will be the mobilisation of "historic" contaminants stored in river sediments during flooding (EEA, 2011). The greater frequency of extreme rainfall events should also augment the transfer of phytopharmaceutical products and veterinary pharmaceuticals to surface waters (Bloomfield *et al.*, 2006; Boxall *et al.*, 2009).

A number of environmental factors such as UV radiation, whose penetration capacity in water depends largely on the pH value and the transparency of the water, two parameters that can be affected by climate change, could even modify the toxicity of certain contaminants by increasing their reactivity through a phenomenon called photo-activation.

Finally, the probable rise of pests, disease and weeds would contribute to worsening the problem due to the more extensive and frequent use of pesticides and veterinary products. However, this increased use could be counter-balanced by augmented volatilisation of certain plant-protection products and accelerated degradation of pesticide residues in soil and surface water due to higher temperatures (Bloomfield *et al.*, 2006).

Over the long term, changes in land use and cover caused by anthropogenic and climate factors will probably have a greater impact on pesticide flows and their transfer to aquatic environments than the direct effects of climate change on the processes controlling the transfer and fate of these pollutants.

Tableau 1 *A few examples of ubiquitous aquatic micropollutants (drawn from Schwarzenbach* et al.*, 2006).*

Origin / use	Class	Substance	Related problems
Industrial chemicals	Solvents	Carbon tetrachloride	Contamination of drinking water
	Feedstock	Methyl tert-butyl ether	
	Petrochemical products	BTEX (benzene, toluene, xylene)	
Industrial products	Additives	Phtalates	
	Lubricants	PCB	Bioamplification in food chains, long-distance cross-border atmospheric pollution
	Flame retardants	Polybrominated diphenyl ethers	
Consumer products	Detergents	Nonylphenol ethoxylates	Endocrine disruption by the degraded product (nonylphenol)
	Pharmaceutical products	Antibiotics	Bacterial resistance to antibiotics
	Hormones	Ethinyl-estradiol	Feminisation of fish
	Personal hygiene products	UV filters	Multiple effects (only partially known)
Biocides	Pesticides	DDT	Toxic effects and persistent metabolites
		Atrazine	Effects on primary producers
	Biocides for non-agricultural use	Tributyltin	Endocrine disruption
		Triclosan	Effects on species not initially targeted, persistent degraded products
Geogenic and natural substances	Trace metals	Pb, Cd, Hg	Risks for human health Impacted quality of drinking water
	Inorganic substances	As, Se, U, fluoride	
	Taste and odour compounds	2-methylisoborneol, geosmin	
	Cyanotoxins	Microcystin	
	Human hormones	Estradiol	Feminisation of fish
Disinfection / oxidation	Disinfection by-products	Trihalomethane, haloacetic acids, bromates	Impacted quality of drinking water, human-health problems
By-products	Metabolites, by-products of chemical substances mentioned above	Metabolites of perfluorinated compounds (PFAS)	Bioaccumulation in spite of low hydrophobicity
		Metabolites of herbicide chloroacetanilides	Impacted quality of drinking water

Conclusion and outlook

As indicated by the historical data, the global climate has always fluctuated over time under the direct and indirect influence of various phenomena (orbital forcing, change in global albedo, disturbances in atmospheric currents, feedback loops). However, human activities, notably the release of greenhouse gasses (GHG), have clearly caused changes in the climate since the end of the 1800s, resulting in increases in air temperatures and the average sea level, as well as a reduction in snow-covered surfaces and ice caps.

In continental France, analysis of long data series has produced estimates of average increases of approximately 1°C in air temperature and 1.6°C in water temperature over the last century. Loss of snow cover at medium altitudes is a further factor confirming that climate change is effectively under way. Other parameters, such as precipitation, evapotranspiration and surfacewater/groundwater hydrology, are also affected but the trends are not as clear given the difficulties in distinguishing between the effects of climate change and those of direct human activities, and because in some cases data series are not long enough.

To assess, over the coming decades, the possible changes in the climate and in the various components of the water cycle (precipitation, evapotranspiration, surface water, groundwater), climate models coupled with hydrological models have been formulated and tested with the various GHG emissions scenarios.

For continental France over the coming decades, all climate projections (whatever the greenhouse-gas (GHG) emissions scenario) foresee warming between 1.5 and 3°C. Longer term, the projections diverge widely depending on the scenario and are much less reliable. They indicate warming from 2°C to more than 4.5°C by 2100.

Concerning water resources, the simulations for precipitation, evapotranspiration and discharges are more uncertain and differ depending on the model. However, evapotranspiration is expected to increase in eastern France. Monthly mean discharges in rivers should decrease and low-flow levels should worsen over large parts of the country, particularly in the southern half. Finally, groundwater recharging may drop along with piezometric levels. Human activities will most likely reinforce the effects of climate change on water resources, notably due to increases in abstractions for agriculture.

Consequently, even though there are numerous uncertainties concerning these projections, the potential impact of climate change on water resources in France should be considerable with a clear trend toward a reduction in those resources. Aquatic environments and fish in particular will be heavily impacted in the above scenarios. This latter point will be the topic of the following chapters.