Weather Extremes and Climate Change

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15-01-2021

in situ

How do extreme weather events change with climate change? Are they becoming more frequent? More intense? Is it man's responsibility? This article presents the state of scientific knowledge on this subject. Recent and future trends in temperature extremes, hydrological extremes, tropical cyclones and extra-tropical storms are discussed, accounting for the uncertainties associated with natural climate variability and numerical modelling. Climate change is already modifying and will continue to modify the probabilities of weather hazards, making some extreme events more frequent and/or intense, and others less so. However, one should not want to hold humans alone responsible for any meteorological event, but rather wonder, in probabilistic terms, how human activities have changed the risk of the occurring event.

1. A difficult link between weather and climate

Heat waves, cold spells, heavy rains, droughts, hurricanes, storms and other **extreme weather events** are regularly in the news, particularly because of their **significant impacts** on societies and the environment. The question of the **link between the occurrence of such events and climate change** is legitimately asked to scientists, and is the subject of increasing work. The answer is not always trivial, especially since the increasingly systematic media coverage of these phenomena and the sometimes increased vulnerability of populations to weather hazards can give a false impression of climate trends.

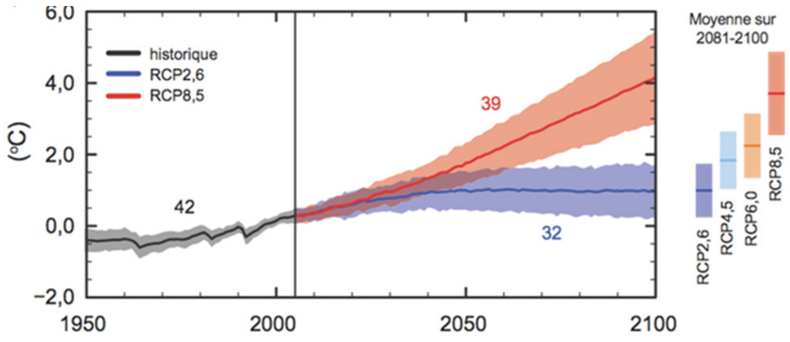

Figure 1. Scenarios for the evolution of the global average temperature (in ºC) based on 4 trajectories of greenhouse gas (GHG) concentration. The zero reference is the average over the end of the 20th century (1986-2005). The uncertainty around each curve includes the choice of climate model and meteorological hazard. The number of simulations used for each scenario and period is indicated. [Source: Figure SPM7 of the 5th IPCC report, ref[1])

In the context of anthropogenic climate change, the scientific challenge is twofold: to **isolate the human footprint** in observed events on the one hand, and to **predict changes into a warmer climate** on the other. This second point is studied using numerical simulations of a future climate, or "climate projections" (Figure 1, [1]). The projections currently used consider four possible trajectories of greenhouse gas concentration for the 21st century ("Radiative Concentration Pathways", RCP), associated with different socio-economic scenarios of greenhouse gas emissions. With the low scenario RCP2.6, the Earth's surface warms by 1ºC (± 0.7) during the 21st century (i.e. by 1.6ºC compared to the pre-industrial period); with the high scenario RCP8.5 by 3.7ºC (± 1.1), i.e. by 4.3ºC compared to the pre-industrial period.

The study of recent or future trends in extreme weather events is generally done for each type of event. Thus, this article will focus successively on temperature extremes, hydrological extremes, tropical cyclones (generic term including hurricanes and typhoons) and extra-tropical storms. We will see that several studies show that **changes are already detectable** in the frequency and/or the intensity of some types of extreme events, and that others may appear or increase during the 21st century. These qualitatively robust results should not mask two **major difficulties in** the study of extreme events:

The first is the **predominant role of** natural climate **variability** in these phenomena, which tends to make the anthropogenic signal unclear and requires high quality observations and/or a large number of simulations to be able to detect changes.

The second is the **imperfect nature of** climate **models**, hence the need to further develop and evaluate them and to rely on a multiplicity of models that are as independent as possible.

2. Temperature extremes

The global warming observed over more than a century affects not only the average temperature, but also the entire statistical distribution of temperatures, i.e. the entire range of possible temperatures in one place and one moment. At the extremes of this distribution are the **rarest events - the cold and hot extremes** - whose occurrence is generally accompanied by significant socio-environmental impacts. Extremes are traditionally defined in terms of their frequency of occurrence, or, in statistical terms, by the quantiles of their distribution. For example, it is common practice to describe a day as unusually hot when its temperature is in the top 10% of the expected values for that day (i.e., it is said to "exceed the 90th percentile - or 9th decile - of the distribution"). By construction, over the period used as a reference, 10% of the days are considered unusually hot. A symmetrical definition is used for abnormally cold days, and the seasonal temperature cycle is generally taken into account, so that we can talk about warm days in winter or cold days in summer. To study the evolution of these extremes, we consider either the evolution of their **frequency** (number of days below or above the current temperature decile) or the evolution of their **intensity,** defined for example as the average temperature of the 10% of extreme days.

2.1. Occurrence of extreme days

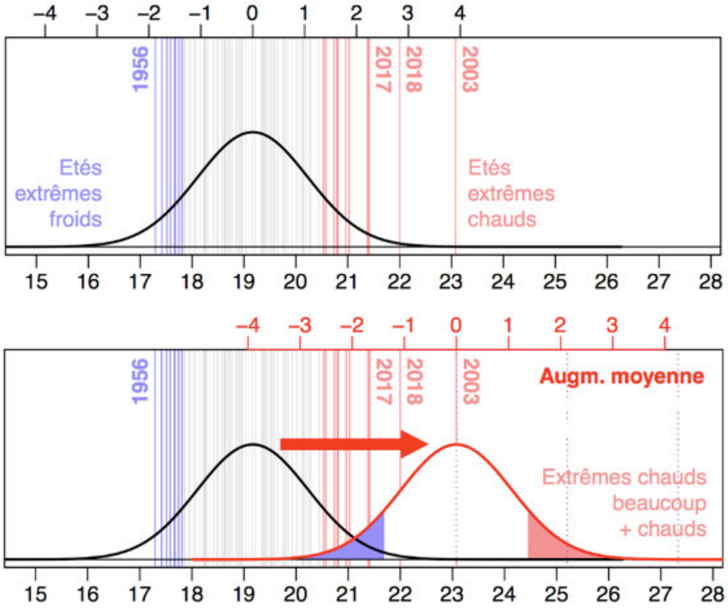

Figure 2. Top: distribution of summer temperature (average June-July-August) in metropolitan France over the period 1900-2018 (Météo-France data). Each vertical line corresponds to one summer: the lower axis gives their temperature (in °C), the upper axis the anomaly of this temperature compared to the average over the whole period (in °C). Extreme cold and hot summers, i.e. those belonging respectively to the first and last deciles of the distribution, are highlighted, particularly the heat waves of 2003 and 2018. The black curve is the Gaussian distribution closest to the data. Bottom: schematic representation of a future change in this distribution, which would follow a simple translation (homogeneous heating from the black curve to the red curve). For the illustration, the future climate is taken as a climate for which summer 2003 would have become the average (cf. new upper axis). [© Julien Cattiaux]

In a warming climate, the entire temperature distribution shifts in case of a leading order translation to warmer conditions (Figure 2). Depending on the definition used for extremes, cold extremes are expected to become less frequent and hot extremes more frequent (for a given temperature threshold), or cold extremes to become less cold and warmer (for a given frequency threshold). And that is what is observed.

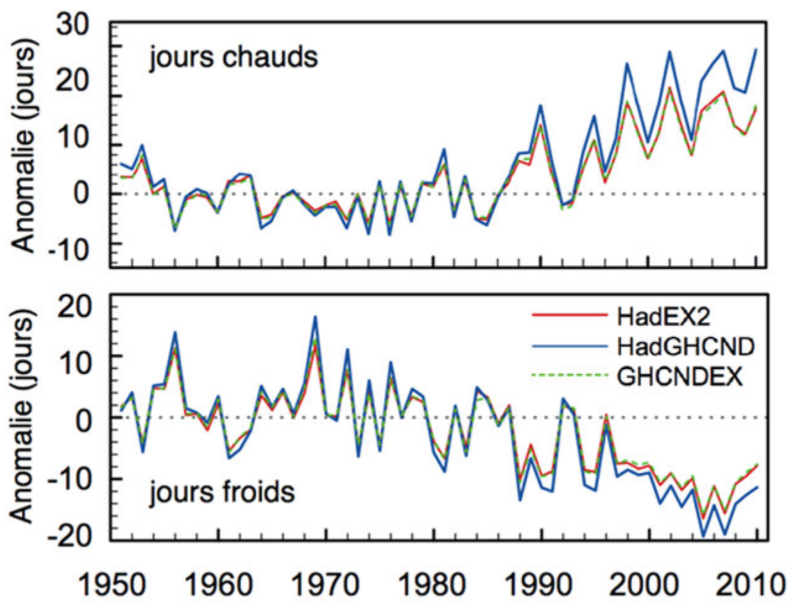

Figure 3. Observed annual frequency of unusually warm (top) and unusually cold (down) days on average over the globe (continents only). A fixed temperature threshold is considered (first and last deciles of the 1961-1990 reference distribution). The curves are centred on the 1961-1990 period and are derived from 3 data sets (colors). [Source: Adapted from Figure 2.32 of the IPCC 5th report, ref.[1]]

On a global scale, there has been a **significant increase in the number of unusually warm days since 1950** (Figure 3,[1]), with hot days more frequent during the 1990ies and the years 2000 than before. Symmetrically, we measure a **decrease in the**

number of unusually cold days. At the same time, there is an overall trend to break more frequently warm than cold daily and monthly records. These results are also observed at the regional level, particularly in Europe.

2.2. Heat and cold waves

Beyond daily statistics, **heat waves** - several consecutive hot days - tend to be **more frequent, more intense and/or longer**, while the number of cold waves has decreased substantially since 1950. While recent heat waves, such as the one in August 2003 in Western Europe, correspond qualitatively to what is expected from a warmer climate, the few **recent winter cold sp**ells observed in Europe (winter 2009/10, December 2010, February 2012) may seem to contradict the idea of global warming.

There is in fact no paradox in the fact that cold episodes can occur locally and occasionally in a context of global warming. This is the **difference between meteorological hazard and a climate trend** on the long term.

Warming is a background process, superimposed on the noise of the natural internal variability of the climate system [read Climate Variability: the example of the North Atlantic Oscillation]. Though variability may continue to cause cold weather events, they are expected to be less frequent and/or less intense due to the global warming [see focus Attribution of singular weather events to climate change: the 2003 heat wave]. Once again, this is exactly what we are seeing: the **coolness of recent cold waves is only relative compared to the freezing winters of 1939/40 and 1962/63, which were** similar in terms of atmospheric circulation.

Finally, it cannot be ruled out that the warming of recent years, which has been particularly pronounced in the Arctic, may have temporarily disrupted the circulation of air masses at our latitudes, and increased the probability of weather situations producing cold waves over Europe. However, this point is still very much debated within the scientific community.

2.3. Evolutions over the 21st century

Whatever the scenario, global warming will continue - more or less strongly - during the 21st century. Thus, not surprisingly, the trends in temperature extremes observed over the recent period are confirmed in climate projections: **hot extremes increasingly frequent and intense, and cold extremes increasingly rare and less marked**. However, the magnitude of these changes is largely dependent on the choice of the greenhouse gas emission scenario. It also varies from one model to another for a given scenario and remains strongly modulated by internal climate variability.

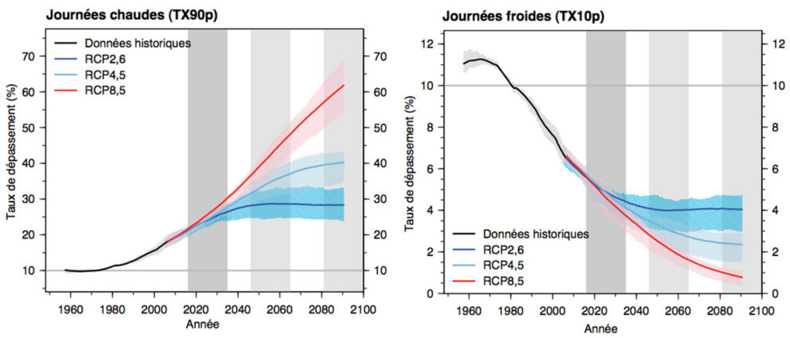

Figure 4. Future projections of the annual frequency of unusually warm (left) and unusually cold (right) days, according to 3 scenarios. The frequency is by definition 10% over the 1961-1990 reference period. [Source: Figure WGI-AT9 of the 5th IPCC report[1]]

On average over the different climate models, and at global and annual scales, the probability of observing a daily temperature above the current 90th percentile thus increases from 10% in the current climate (one day in ten, by construction) to 25% (one day in four) in scenario RCP2.6, or even 60% (more than one day in two) in scenario RCP8.5, by 2100. Conversely, the frequency of unusually cold days falls to 4% in RCP2.6 and 1% in RCP8.5 (Figure 4). This evolution also affects very rare events: for example, **a hot event that occurs on average every 20 years** in the current climate - referred to as a return period of 20 years - **would occur on average every other year by 2100 in RCP8.5**. In the same scenario, its cold equivalent has its return period increasing from 20 years to more than a century. Despite these trends, the occurrence of extreme cold is still possible. Even in a strong scenario, it is to be **expected that some cold records will be broken locally in the 21st century**, but much less frequently than warm records. For example, in the United States, the ratio between the occurrence of hot records and the occurrence of cold records is currently 2:1: it is estimated at 20:1 around 2050 and 50:1 in 2100 in the moderate scenario.

In addition to the **uncertainties associated with the scenario selection and with the internal climate variability**, the future evolution of temperature extremes is sensitive to **the choice of the numerical** climate **model**, particularly at regional and seasonal scales. In Europe, in the RCP8.5 scenario, the probability of exceeding the current 90th percentile (or 9th decile) of summer temperature - which is by construction 10% on the current climate - ranges from 30% to 90% depending on the model on average over the future summers 2070-2100.

These uncertainties also affect the characteristics of multi-day events. For example, although future projections agree on the increase in the frequency, intensity and duration of European summer heatwaves, their **evolution by 2100 varies by a factor of three, for a given scenario, depending on the numerical model considered**.

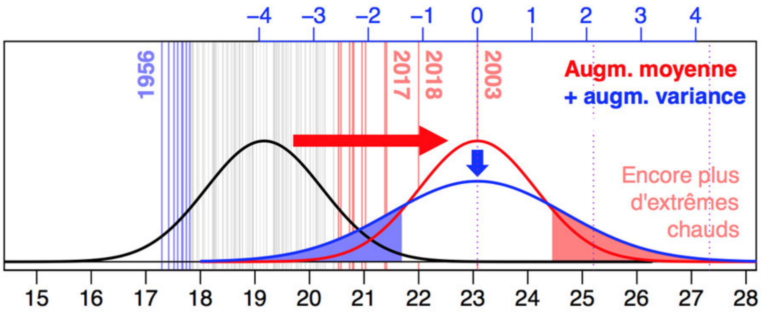

Figure 5. Schematic representation of a change in the summer temperature distribution in France with, in addition to a simple translation (warming, from black to red curves, see Fig. 2), a widening (increase in variability from black to blue curves). In this latter case, the probability of hot extremes further increases. Same legend as Figure 2. [© Julien Cattiaux]

Finally, if changes in temperature extremes primarily depend on the amplitude of the mean warming (shift of the distribution), they are **modulated by changes in variability (distribution shape and width**, see Figure 5). In Europe, future projections suggest a small increase in variability in summer, making warm extremes even more likely, and a small reduction in winter, making cold extremes even less likely. These behaviours are respectively linked to a drying of the soil in summer and a decrease in snow cover in winter.

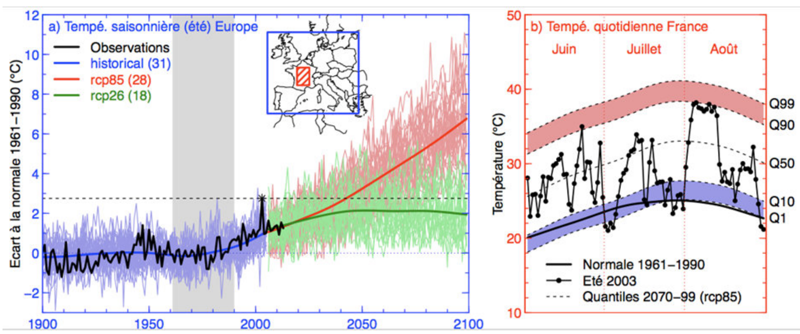

Figure 6. a) 1961-1990 departure from normal summer temperature (June, July, August) in Europe (blue rectangle on the map) for observations (black curve), historical simulations (31 model simulations, blue curve) and future simulations with RCP2.6 (18 model simulations, green curve) and RCP8.5 (28 model simulations, red curve) scenarios. The averages are indicated by thicker lines. The anomaly observed in 2003 (2.8°C, marked by a star and the dashed threshold) becomes cold in RCP8.5 from 2040 onwards, but remains warm in RCP2.6 until 2100. b) Daily temperature of the 2003 summer (black circles) averaged over central France (red hatched rectangle on the map), compared to the observed mean temperature over 1961-1990 (thick black curve) and to the distribution of percentiles over 2070-2099 in all RCP8.5 simulations (blue zone delimited by the first and tenth percentiles for cold days, red zone by the 90th and 99th percentiles for warm days, see scale on the right). Early August 2003 would remain warm at the end of the century, even in this (strongest) scenario. [Source: Figure by Boucher et al., ref.[2])

Is the 2003 hot summer a prototype of the 21st century European summers? At the scale of Western Europe and for the summer season, the 2003 heat wave has a temperature anomaly of around 3°C compared to the 1961-1990 average temperature. **It corresponds to an average summer of the 2040s and even becomes an extreme cold one in 2100, according to the RCP8.5 scenario** (Figure 6a, [2]). However, in the RCP2.6 scenario it remains an unusually hot summer until 2100 . Moreover, locally (in France) and on a scale of a few days, the hottest days of August 2003 remain unusually hot even in 2100 in the RCP8.5 scenario (Figure 6b, [2]). The answer therefore depends on the scenario and on the spatial and temporal scale considered.

3. Hydrological extremes

Apart from the temperature increase, the increase in the greenhouse effect is likely to **disrupt the global hydrological cycle** (water exchanges between the atmosphere, the ocean and continents; read: Are we at risk of water shortage?) and its extreme events (heavy rainfall and droughts in particular), for several reasons:

Surface warming **promotes evaporation**, especially in regions where water is always available (oceans and humid continents).

In accordance with the Clausius-Clapeyron relationship (read Thermodynamics a plot of a rising air parcel in a cumulonimbus), a warmer atmosphere has its maximum water vapour content increased by about 7% per degree of warming, potentially allowing a **larger atmospheric water reservoir** to be mobilized in a warm climate when weather conditions are favourable to precipitation.

Finally, rainfall patterns can be impacted by **possible changes in atmospheric circulation** since it is this circulation that transports most of the water vapour that will contribute to precipitation in a given location.

The response of hydrological extremes is **particularly difficult to understand** because of its spatio-temporal heterogeneity and of the **direct influence (apart from climate change) of humans on continental water flows and storage**.

Available observations show that there is already an increase in the number and/or intensity of heavy rainfall in some regions of the world, particularly in Europe and North America where relatively long measurement series are available. For France, no systematic assessment of extreme precipitation trends is yet available.

3.1. "Mediterranean events"

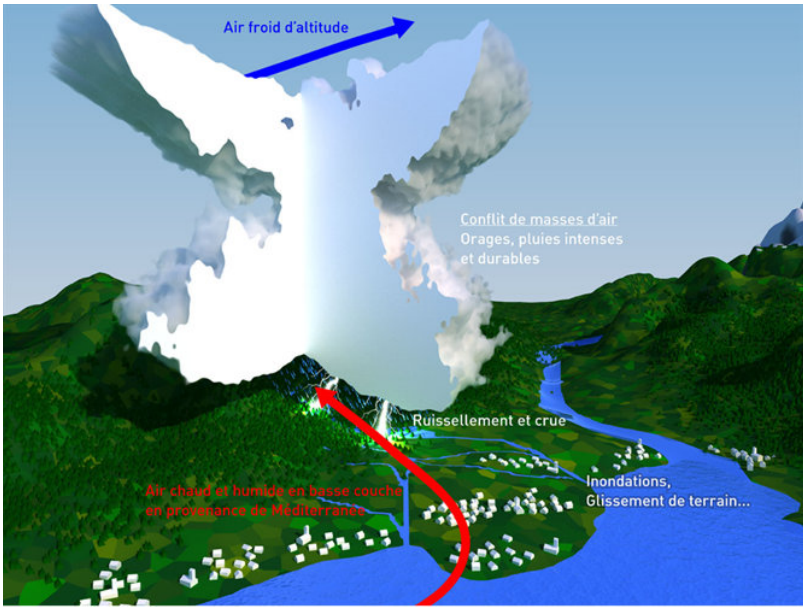

Figure 7. Illustration of a Mediterranean rainfall event [Source: Météo-France].

In the presence of a very humid Southerly to South-Easterly wind regime, the "Mediterranean events" observed in south-eastern France correspond to the highest precipitation events in mainland France (Figure 7). They are the subject of particular attention and some studies suggest a recent intensification of these events. However, it is more difficult to translate these changes into floods, as they are highly subject to increasing anthropogenic impacts (e.g. urbanisation, deforestation, agriculture) in many catchment areas (this is even more true at the global scale).

3.2. Droughts

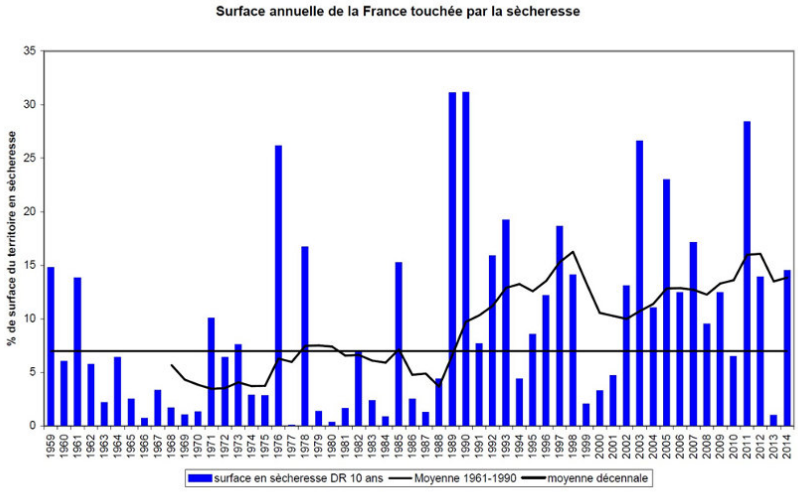

Figure 8. Percentage of the French metropolitan territory affected by agricultural drought each year. The criterion used here is the first decile of soil moisture over the period 1961-1990, based on re-analysis data. [Source: © Météo France, Result of the ClimSec project, see Ref.[3]]

Droughts are caused by a more or less persistent water deficit. To characterize them, **indicators** are used. Meteorological droughts are the easiest to describe and show **disparate trends** from one region to another, sometimes largely influenced by natural climate variability (in Sahel or more recently in California for example). Recent trends in agricultural droughts are more difficult to assess in the **absence of a global network of *in situ* measurements** and despite progress in spatial observation. An alternative is to **simulate the evolution of soil water content** in response to observed variability in meteorological parameters. This method implemented by Météo-France on the metropolitan territory shows an **increase in soil droughts in several regions** since 1958 (Figure 8), particularly in the Mediterranean regions but also in West France [3].

3.3. Future global hydrological changes

Future projections suggest some **qualitatively robust changes**, including an **increase in spatial and temporal contrasts in precipitation** around the globe, often summarized by the motto "*wet get wetter, dry get drier*". If this pithy motto is still the subject of debate within the scientific community, the drying up of the Mediterranean basin and more generally a poleward expansion of arid and semi-arid zones seems inevitable. As a result, the contrast between the European North (wettest) and South (driest) is expected to increase, and some recent work even suggests that most numerical climate models underestimate the summer drying of the northern hemisphere mid-latitudes.

These models also indicate a **relatively widespread intensification of heavy precipitation events** in response to global warming, including in areas that will experience an average drying. The exceptions to this increase in extreme rainfall are mainly in subtropical regions. In the simulations, this intensification of heavy rainfall is all the more pronounced as the scenario of increasing greenhouse gas concentrations is high. Also, the shorter the period of analysis of precipitation accumulation (daily to hourly accumulations), the more frequent and intense heavy precipitation is projected to be. This intensification occurs at a rate that sometimes exceeds the 7% per degree of average warming predicted and observed for atmospheric water vapour. However, these numerical results should be considered with caution due to the limited horizontal resolution of most models and their simplified representation of the processes associated with these extreme events.

The expected intensification of the hydrological cycle in warmer climates also results in an **increased risk of drought** in many parts of the world, including some regions where the average annual precipitation increases during the 21st century. This is due both to an increase in the temporal variability of precipitation (increase in the number of consecutive days without rain) and to an **increase in evapotranspiration** (evaporation of continental surfaces and transpiration from plants to the atmosphere). In summary, global warming therefore affects both ends of the precipitation distribution, making both intense rainfall events and drought episodes more likely.

Mediterranean-type climates (around the Mediterranean, but also some regions of Australia, South Africa, or America) **are likely to be particularly affected** by these hydrological changes, while more generally, a shift of arid zones towards mid-latitudes is expected. Although oversimplified, the paradigm "rich get richer, poor get poorer" thus reflects a **predictable increase in inequalities in the climatic water supply**. In France, a decrease in the quantity of water available in the soil is expected, as well as a decrease in the low levels of most rivers.

4. Tropical Cyclones

Tropical cyclones, also known as hurricanes (in the Atlantic) or typhoons (in the Pacific), are **by far the most devastating meteorological events**, both in terms of their power and of the population affected (read Tropical Cyclones: development and organization and Tropical Cyclones: impacts and risks). It was **only since the 1970s that a systematic observation of cyclones has been possible** with the advent of satellites. Thus, any trend estimated over the entire 20th century is questionable (Figure 9).

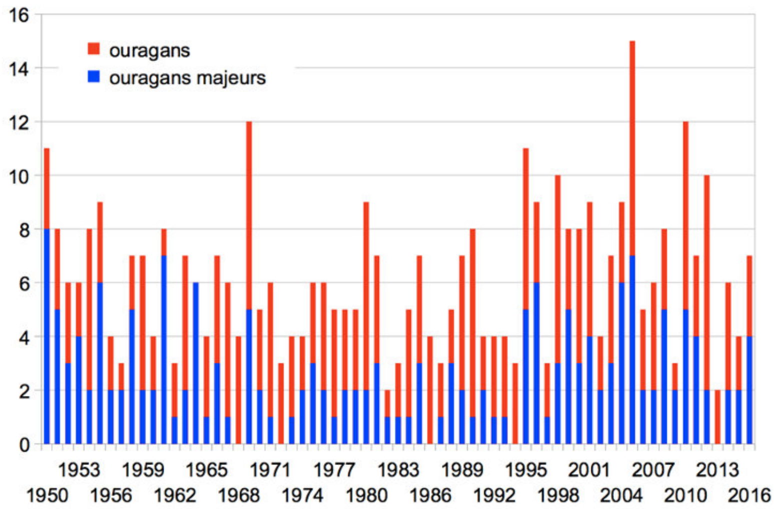

Figure 9. Annual number of tropical cyclones or hurricanes in the Atlantic (categories 1 to 5 on the Saffir-Simpson scale), and of the strongest hurricanes (categories 3 to 5 on the same scale). Data from the Hurricane Research Division of the United States Federal Oceanic and Atmospheric Administration (NOAA). [© Gilles Delaygue]

In addition, the observed cyclones observed are sensitive to natural climate variability affecting the ocean basins. The relative calm of cyclonic activity in the Atlantic basin during the 1970s and 1980s is probably linked to a cold phase of the Atlantic multi-decadal Oscillation (AMO), which also contributed to the major droughts in the Sahel at that time. This mode of variability corresponds to an oscillation of sea surface temperature anomalies in the North Atlantic on a time scale of several decades. The decades that followed were marked by greater hurricane activity in the Atlantic Ocean, which is difficult to compare with the previous positive phase of the AMO due to the lack of quality data, particularly satellite data. Thus, it is not easy to calculate long-term trends in tropical cyclone activity based on past observations. Some studies have attempted to highlight upward trends in the most intense cyclones over the past 40 years, but there has been little consensus in the scientific community.

Modelling tropical cyclones faces the difficulty of representing these phenomena in numerical climate models. Indeed, their small size (from a few tens to several hundred kilometres) requires the use of climate simulations on very fine calculation grids (around 50 km) in order to represent them realistically. The grid of a model can be thought of as a network of points of which the mutual distance limits the size of the smallest phenomenon that can be simulated.

Despite this limitation on their simulation, the work carried out to date converges on the trend of cyclonic activity for the end of the 21st century. Thus, climate models suggest that the total number of tropical cyclones would remain stable or even decrease in warmer climates, as conditions conducive to their onset would become somewhat rarer. On the other hand, once triggered, cyclones draw their energy from the heat content of the first 50 metres of the surface ocean. In a warmer world, the strongest cyclones would therefore see their intensity increase: stronger maximum winds and more intense associated rains. Cyclone Irma, which hit the islands of Barbuda, St. Martin and St. Barthélemy in 2017 as a category 5 cyclone (cover image), is a good example of these most intense cyclones, whose probability of occurrence is expected to increase with warming in the Atlantic basin. The most recent work also indicates a possible extension towards the poles (beyond the tropics) of regions affected by tropical cyclones.

It should also be borne in mind that the damage caused by cyclones does not only depend on their intrinsic characteristics (intensity, trajectory, etc.), but also on associated phenomena, such as storm surge. The observed sea-level rise, projected for the 21st century, thus makes coastal regions increasingly vulnerable to cyclonic phenomena by submersion, such as the one caused by Cyclone Pam in 2015 in Vanuatu. In addition, a trend that seems to be well marked in climate projections concerns the intensity of rainfall associated with cyclonic phenomena. This intensity shows a significant increase in models for the end of the 21st century, sometimes beyond the 7% per degree of warming suggested by the Clausius-Clapeyron formula. The latter aspect of tropical cyclones is particularly important in a context where coastal cities are becoming denser and thus more vulnerable to flood risks. Recently, Cyclone Harvey (August 17 to September 2, 2017) dramatically illustrated the effects of heavy cumulative rainfall over the life of the system, worsened by the stagnation of the system over the city of Houston.

5. Extra-tropical storms

Storms - and more generally atmospheric circulation - in mid-latitudes are **related to the temperature difference between the equator and the poles** (read Atmospheric circulation: its organization). Their recent and future evolution therefore depends on the meridional contrasts of global warming. In the Northern Hemisphere, at the surface, the recent and projected melting of the Arctic ice pack results in a more pronounced warming at the pole, which reduces the temperature gradient between the pole and the equator. On the other hand, warming peaks at the top of the troposphere (about 10 km above sea level), reinforce this same gradient. The evolution of the atmospheric dynamics of the mid-latitudes, including depressions and storms, therefore depends on the competition in warming between these two regions, i.e. the upper tropical troposphere against the lower Arctic troposphere. More regional factors, such as the distribution of warming over the North Atlantic, can also modulate the evolution of lows over Europe. If we add to this the great natural variability of the climate system at these latitudes (read Climate variability: the example of the North Atlantic Oscillation), and the fact that only a fraction of the depressions evolve into real storms, we can understand that **with the current state of knowledge, the effect of global warming on these phenomena remains very uncertain**.

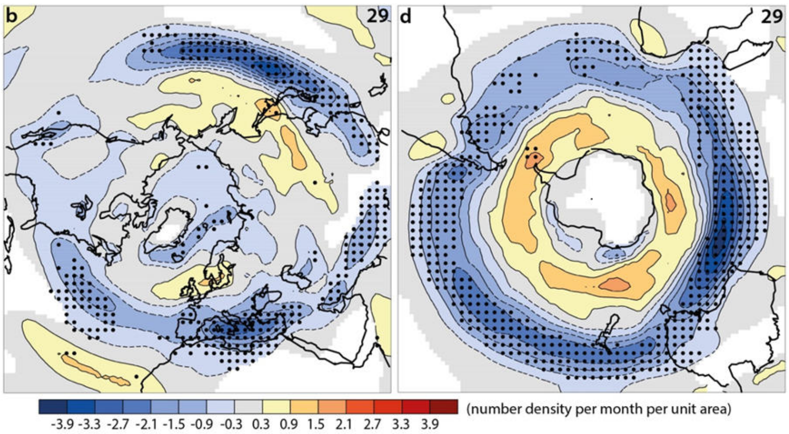

Figure 10. Projections of the change in frequency of winter storms in the northern (left) and southern (right) hemispheres, between the present climate 1986-2005 and the future climate 2081-2100 with the RCP8.5 scenario. In the southern hemisphere, models predict a decrease at mid-latitudes and an increase at higher latitudes: this reflects a poleward shift of storm tracks towards the South Pole. In the northern hemisphere, this signal is less clear, as it is offset by the particularly intense surface warming of the Arctic. The dotted regions are those where the used 29 models agree on the sign of change. [Source: Adapted from Figure 12.20 of the 5th IPCC report]

Studies based on atmospheric observations and re-analyses have nevertheless shown an increasing trend in the number of storms over Scandinavian countries during the 20th century. For **other regions, particularly France, no reliable trends have** been identified in the past. In the 21st century scenarios, while a majority of numerical models seem to favor a poleward shift of the activity of mid-latitude lows towards the poles (especially in the southern hemisphere) (Figure 10). In view of the complexity of the involved phenomena, this trend should still be considered with caution. It is therefore still too early to draw conclusions on the influence of anthropogenic warming on extra-tropical storms. However, it can be expected that the associated precipitation will be more abundant, due to the humidification of air masses and in accordance with the Clausius-Clapeyron relationship already mentioned above.

6. Conclusions: More frequent or intense extreme phenomena

The study of extreme weather events is a major scientific and societal challenge. **Climate change is already modifying and will continue to modify the probabilities associated with weather hazards**. But these changes do not always go in the same direction, as some oversimplified, alarmist or climatosceptical messages sometimes suggest. Thus, while global warming **makes some extreme events more frequent and/or intense** (heat waves, intense rainfall episodes, droughts), **others are less likely** (cold waves). The scientific message may even be more complicated:

For cyclones, the state of knowledge suggests a slight decrease in the total number but an increase in the number of cyclones of the strongest categories.

As for mid-latitude storms, their evolution with climate change remains largely uncertain (which does not mean "misunderstood").

Beyond the knowledge already acquired, many scientific questions remain. The World Climate Research Programme has made this topic one of its priorities for the next decade. This challenge has multiple dimensions such as the establishment, operation and/or homogenization of the observation network, the improvement of numerical climate models and the evaluation of their ability to simulate extreme events, the development of statistical tools to detect, attribute and understand their climatic evolution, and research on their predictability at different time scales (season, decade, etc.).

Finally, it should be reiterated that even though climate change is expected to affect extreme weather events, it should not be systematically blamed when an event occurs. More specifically, we should not want to hold humans alone responsible for some meteorological event, but rather wonder, in probabilistic terms, how human impacts have **changed the risk of the event**.

7. Take home messages

Human-induced climate change is already modifying and will continue to modify the probability of weather hazards.

Most extreme events (e.g. heat waves, heavy rains, cyclones) become more frequent and/or intense, some become less likely (e.g. cold waves), while for others, the signals are contrasted (e.g. storms).

Humans cannot be held solely responsible for any observed event; on the other hand, we can estimate how human impacts have modified the probability of the event.

Climate variability and the heterogeneity of historical data make it difficult to detect trends in observations.

Improved numerical climate modelling tools will reduce the uncertainties associated with the future evolution of extreme events.

Notes and references

Cover image. Hurricane Irma on the Lesser Antilles (Sept. 6, 2017) [Source: © NASA/Goddard Space Flight Center Earth Science Data and Information System (ESDIS) project.]

[1] Intergovernmental Panel on Climate Change (IPCC), 2013, Fifth Assessment Report, Scientific Elements, Contribution of Working Group I (http://ipcc.ch/report/ar5/wg1/).

[2] Boucher et al (2015) Projection of future climate change, La Météorologie, n°88, p.56-68. Doi: 10.4267/2042/56362

[3] ClimSec project. See Soubeyroux et al (2012) Soil droughts in France and climate change: Results and applications of the ClimSec project. La Météorologie nº78, p.21-30. doi: 10.4267/2042/47512 and CNRM website: https://www.umr-cnrm.fr/spip.php?article605&lang=en

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L'Encyclopédie de l'environnement est publiée par l'Université Grenoble Alpes - www.univ-grenoble-alpes.fr

Pour citer cet article: **Auteurs :** CATTIAUX Julien - CHAUVIN Fabrice - DOUVILLE Hervé - RIBES Aurélien (2021), Weather Extremes and Climate Change, Encyclopédie de l'Environnement, [en ligne ISSN 2555-0950] url : http://www.encyclopedie-environnement.org/?p=6749
