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Expected impacts of climate change on extreme climate events

Serge Planton [a,*], Michel Déqué [a], Fabrice Chauvin [a], Laurent Terray [b]

[a] *Météo-France, centre national de recherches météorologiques/groupe d'étude de l'atmosphère météorologique (CNRM/GAME), 42, avenue G.-Coriolis, 31057 Toulouse cedex 1, France*
[b] *Centre européen de recherches avancées en calcul scientifique, 31057 Toulouse cedex 1, France*

Abstract

An overview of the expected change of climate extremes during this century due to greenhouse gases and aerosol anthropogenic emissions is presented. The most commonly used methodologies rely on the dynamical or statistical downscaling of climate projections, performed with coupled atmosphere–ocean general circulation models. Either of dynamical or of statistical type, downscaling methods present strengths and weaknesses, but neither their validation on present climate conditions, nor their potential ability to project the impact of climate change on extreme event statistics allows one to give a specific advantage to one of the two types. The results synthesized in the last IPCC report and more recent studies underline a convergence for a very likely increase in heat wave episodes over land surfaces, linked to the mean warming and the increase in temperature variability. In addition, the number of days of frost should decrease and the growing season length should increase. The projected increase in heavy precipitation events appears also as very likely over most areas and also seems linked to a change in the shape of the precipitation intensity distribution. The global trends for drought duration are less consistent between models and downscaling methodologies, due to their regional variability. The change of wind-related extremes is also regionally dependent, and associated to a poleward displacement of the midlatitude storm tracks. The specific study of extreme events over France reveals the high sensitivity of some statistics of climate extremes at the decadal time scale as a consequence of regional climate internal variability. *To cite this article: S. Planton et al., C. R. Geoscience 340 (2008).*

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Résumé

Impacts du changement climatique sur les événements climatiques extrêmes Nous présentons, dans cet article, une revue des changements attendus au cours de ce siècle sur les extrêmes climatiques, du fait des émissions anthropiques de gaz à effet de serre et d'aérosols. Les méthodologies les plus couramment utilisées reposent sur la descente d'échelle dynamique ou statistique des projections climatiques réalisées à partir de modèles de circulation générale atmosphériques et océaniques couplés. Qu'elles soient de type statistique ou dynamique, les méthodes de descente d'échelle présentent des forces et des faiblesses, mais ni leur validation sur les conditions du climat actuel, ni leur capacité potentielle à projeter l'impact du changement climatique sur les statistiques des événements extrêmes ne permet de donner un avantage spécifique à l'un des deux types. Les résultats synthétisés dans le dernier rapport du GIEC et des études plus récentes soulignent une convergence, pour une très probable augmentation des épisodes de vague de chaleur au-dessus des surfaces continentales, liée au réchauffement moyen et à l'augmentation de la variabilité de la température. De plus, le nombre de jours de gel devrait décroître et la saison de croissance s'allonger. L'accroissement projeté des événements de

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* Corresponding author.

E-mail address: serge.planton@meteo.fr (S. Planton).

précipitations intenses apparaît aussi très probable sur la plupart des régions et semble aussi lié à un changement de la forme de la fonction de distribution de l'intensité des précipitations. Les tendances globales sur la durée des sécheresses sont moins cohérentes entre les différents modèles ou suivant les différentes méthodes de descente d'échelle, du fait de leur variabilité régionale. Les changements des extrêmes liés au vent sont aussi dépendants de la région et sont associés à un déplacement, vers les poles, des trajectoires des dépressions des moyennes latitudes. L'étude spécifique des événements extrêmes en France révèle la forte sensibilité de certaines statistiques des extrêmes climatiques à l'échelle de temps décennales du fait de la variabilité interne du climat à l'échelle régionale. ***Pour citer cet article : S. Planton et al., C. R. Geoscience 340 (2008).***

1. Introduction

The increase in the frequency or intensity of extreme events is commonly associated to climate change due to greenhouse gases and aerosol anthropogenic emissions. The shift of the probability density function (PDF) of a climatic parameter towards one side of the distribution would indeed induce an increase in the probability of occurrence and of the intensity of the extremes that are on the same side. This is the reason why, for example, warming should induce an increase in the intensity and frequency of heat waves, and the decrease in mean precipitation in summer should have the same impact on drought episodes. The shift of the PDF will have also the reverse effect on the occurrence and intensity of cold days and intense precipitation. However, these results might be different when climate change is accompanied by a change of the shape of the PDF. This change has been observed in the recent past in the case of temperature for some regions, as reported in the last IPCC Fourth Assessment Report or AR4 [15]. The analysis of daily temperature series in France also shows that daily maximum temperatures in summer have experienced an increase in variance over the second half of 20th century [9]. This implies that the shift of the corresponding PDF towards warmer values is associated to a widening of the distribution that increases the severity of hotter extremes, but limits the change of the statistics of the coldest events. Schär et al. [20] have also advocated that only an increase in the variability of summer temperature in Europe could account for the occurrence of the 2003 heat wave. Whether future climate change will confirm or not these trends, is a key question that has been addressed only recently.

The extremes that are generally considered in the impact studies of climate change are either rare, typically corresponding to the 10th or 90th percentile (thresholds with 10% of values lower or higher), intense even if not rare, or severe through their consequences (see for example, Beniston et al. [2]). There are, of course, many possible definitions of extreme events, leading to some difficulties in comparing different analyses. This is the reason why climate scientists have tried to give some guidance for the selection of indices of extreme climate events. Following the recommendations of international working groups, Frich et al. [13] proposed a first set of 10 indices based on series of daily maximum and minimum temperature, and of total precipitation. These indices were chosen for their robustness, leading to the retention of relatively moderate extremes rather than paroxysmal ones in order to avoid a too noisy behavior. These indices have also the great advantage of being easily computable from observed or simulated series. They served as a basis for a more complete set of indices of climate extremes that was proposed in the context of the STARDEX European project [14]. Either the initial list of indices given by Frich et al. or that of the STARDEX project have been used in different studies on the impact of climate change on extremes that we summarize in the following.

In the next section we will first expose the methodologies that are commonly used to evaluate the impact of climate change on extremes. We also give some insights on the performance of these methods when they are applied to present climate conditions. In section 3 we present an overview of some recent results on the expected climate extremes all over the globe. This includes a brief review of IPCC AR4 regarding this aspect of climate change. This also includes a synthesis of some more recent studies that have analyzed either global climate simulations performed in the context of IPCC AR4 or the downscaled outputs of global coupled atmosphere–ocean general circulation models (AOGCM). In section 4, we focus on results that were obtained in the context of the so-called IMFREX project [9] completed with original findings that all put emphasis on the impact of climate change on extreme events over France.

2. Methodologies and their validation

The projection of future climate change at the scale of the century relies on the use of climate model simulations that represent the only way to account for the complex interactions and feedback between and within the different components of the climate system. However, climate simulations are limited by the ability of the models to accurately reproduce the statistics of some extreme events. According to the most recent studies, such as those reported in [15], as far as temperature is concerned, the global statistics of observed extreme temperature are generally well simulated by the AOGCM. A study of the atmospheric component of such models conducted in the context of the "Atmosphere Model Intercomparison Project" (AMIP) concludes that, on average over several decades, these atmospheric models simulate temperature extremes reasonably well, but with a greater disagreement for cold extremes, particularly in cloudy regions [17]. This fairly good agreement between model simulations and observations is not only true on average, but also for trends over the second part of the 20th century. Christidis et al. [7], indeed, compared observed patterns of change in the warmest nights of the year, for a late period relative to an early period of the last 50 years of this century, with those simulated with different coupled models and forcing conditions (natural and anthropogenic). They show, through a formal optimal detection analysis, a significant robust human influence on the observed pattern of changes in extremely warm nights. This result proves the ability of the given models to reproduce those changes. As far as precipitation is concerned, the statistics of extreme events are less reliably reproduced by models than those of extreme temperature [15]. The intercomparison study of the atmospheric components [17], also reveals that the largest disagreement occurs in the tropics due to the difficulty of the models to represent the deep convection process. The majority of these models underestimate the amplitude of the 20-year return values of annual precipitation extremes. They have also a general tendency to overestimate the frequency of low precipitation events that implies an inadequacy in the reproduction of dry spells. Contrary to temperature extremes, there is no reported successful detection of anthropogenic influence in the observed trends of precipitation extremes.

One main limitation of AOGCM in the reproduction of precipitation extremes comes from their low resolution that is often insufficient to reproduce accurately the meteorological events that produce them. This is particularly the case for tropical storms or cyclones or for convective events for which spatial scales are incompletely, or even not at all, resolved by these models (see also the paper of André et al. in this issue [1]). One way to extend the domain of validity of models consists in simulating one region of interest with a high resolution, and, more often, an uncoupled, regional climate model (RCM). Since, for climate projections, the boundary conditions of this model – at the sea surface and at the frontiers of the domain for a limited area model – need to be specified from a global AOGCM, this method is equivalent to a downscaling of the information given by this global model. The forcing of the regional climate model is thus specified through these boundary conditions, but also through prescribed greenhouse gases and aerosol atmospheric concentrations consistent with those of the global model. This approach is referred to as a "dynamical downscaling" since it relies on the simulation of climate processes at a finer scale than that provided by the driving AOGCM. A recent analysis by Frei et al. [12] evaluated precipitation extremes simulated by six European RCM thanks to a dataset collected over the Alps. They took advantage of two European projects, the first one providing the database of RCM simulations (PRUDENCE [6]) and the second standardized statistics to characterize the extreme events (STARDEX [14]). They also used the statistical theory for extreme events as recommended by Katz [16] and applied it for the first time to climate simulations by Zwiers et Kharin [24]. The main advantage of this theory is that it extends the range of the diagnostics on extreme events to return values of the order of the length of the simulations, i.e. a few decades. The evaluation of Frei et al. demonstrates that, contrary to AOGCM, RCM are successful in reproducing mesoscale patterns of observed precipitation extremes that are constrained by the orography. The model's performance for rare extremes is not worse than for mean wet day intensity with the greater discrepancies – of the order of a few tens of percent – occurring for the summer season.

An alternative to "dynamical downscaling" is the "statistical downscaling" (SD) that relies on statistical relationships between selected large scale predictors and regional scale predictands. The general principle is to establish a link between the simulated large scale and the finer scale of extreme events using one or a combination of statistical models calibrated on observational datasets (regression, neural networks, weather generator, weather types, analogues...). Many studies applying SD have been performed these last years, but only a few compared their performances with those of

RCM, in reproducing climate extremes statistics on present climate conditions [15]. Schmidli et al. [21] have recently compared the ability of a set of six SD methods and three RCM, to reproduce extreme precipitation over the Alps for present climate conditions (1979–1993). They conclude that, whatever the method, the occurrence of the events is substantially better reproduced than the intensities and that summer is here again the season with the lowest skill. The biases are, in general, of comparable magnitude for the better RCM and the better SD methods. However, while SD methods appear to reproduce better the location of maxima compared to RCM, they tend to underestimate the interannual variability. This specific study confirms in the case of the analysis of extreme events the general statement of IPCC that SD methods and RCM are comparable for simulating current climate [15].

The direct comparison of the downscaled extremes to observations allows identifying some weaknesses and strengths of the different methods, but it is not sufficient to assess their ability to predict the impact of climate change on these extremes. One hypothesis of SD methods is that the basic statistical models are stationary and are thus not affected in their structure by climate change. This appears as a much stronger hypothesis than the stationary hypothesis applied to the theoretical and empirical laws describing the processes at work in the climate system and included in the RCM. However, these RCM also very often need bias corrections inferred from a direct comparison of the simulated climate to the observed one. In current applications, the corrections are also supposed stationary and independent of climate change [8]. It is thus not possible to give an advantage to dynamical downscaling only arguing on the stationary hypothesis used for statistical models. A common limitation also often reported concerning the most part of the SD methods, is their general tendency to underestimate climate variability (see above). Von Storch [22] has pointed out the origin of this common feature and has proposed a way to cope with it, adding noise to the predictands. Whether this has a specific impact on low frequency variability of climate extreme statistics is difficult to investigate due to the lack of long-term homogeneous data series. Here again, we cannot argue on this to give more confidence in the dynamical downscaling approach.

In practice, the two types of methods are not always applied in parallel but may be used in combination. In some applications, this has the advantage of profiting by an improved representation of large-scale circulation with an RCM compared to the driving AOGCM, but keeping the advantage of SD methods that allow generating series of climate parameters at a finer scale [3].

3. Future extreme events at the global scale

The IPCC AR4 includes a synthesis of the expected change on climate extremes derived from the scientific literature before mid-2006 [15]. A first part of this synthesis concerns the results obtained from the analysis of AOGCM results. It confirms previous status on this subject concerning a very likely (probability greater than 90%) increase in some extreme events such as heat waves and heavy precipitation at the end of 21st century ([11] and Table 1). Tebaldi et al. [23] analyzed some diagnostics on extreme events derived from simulations of climate change over the 20th and the 21st century, performed with nine AOGCM that contributed to the IPCC AR4 multimodel ensemble of simulations. They choose to characterize the temperature and precipitation extremes through the indices proposed by Frich et al. [13]. They find that future trends on the

Table 1
Recent trends, assessment of human influence on the trends, and projections for extreme weather events. Extracted from [15], Table SPM-2
Tendances récentes, évaluation de l'influence humaine sur ces tendances et projections d'événements météorologiques extrêmes. Extrait de [15]*, Tableau SPM-2*

Phenomenon and direction of trend	Likelihood that trend occurred in the late 20th century (typically post-1960)	Likelihood of a human contribution to observed trend	Likelihood of future trends based on projections for the 21st century using SRES scenarios
Warm spells/heat waves. Frequency increases over most land areas.	Likely	More likely than not	Very likely
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	More likely than not	Very likely
Area affected by droughts increases	Likely in many regions since the 1970s	More likely than not	Likely

global averages of the extreme indices correspond to an amplification of the trends simulated by the models for these averages at the end of 20th century. They also point out that the dominant patterns of change with significant strength at the end of 21st century are also present at the end of 20th century. This applies to all the indices with a greater consistency for temperature-related extremes (negative trend for the total number of frost days and the intra-annual extreme temperature range, positive trend for the growing season length, the heat wave duration and the number of warm nights) than for precipitation related ones (positive trends for the number of days with precipitation greater than 10 mm, the maximum number of consecutive dry days, the maximum five-day precipitation total, the daily precipitation intensity and the fraction of annual total precipitation due to events exceeding the 1961–1990 95th percentile). This supports the detection of an anthropogenic signal in some extremes already mentioned above. However, in the absence of formal detection analysis of observed data series based on specific statistical methods like the so-called "fingerprint method", the expert judgement of IPCC states as only "more likely than not" (a probability greater than 50%) the fact that observed trends in heat waves, heavy precipitation and drought have a human-induced component.

Concerning temperature-related extremes, the trends are only weakly dependent on the SRES emission scenario (the so-called B1, A1B and A2 scenarios, from the lowest to the most severe in terms of cumulative greenhouse gases emissions) at least until around 2040. The spatial patterns of change are also very consistent across scenarios and across models, showing different "hot spots" that include high latitudes of the northern hemisphere for most of the indices, and eastern Europe for the larger increase in growing season and decrease in frost days. Generally speaking, the changes in the indices follow the mean temperature change but are regionally modulated by changes of circulation and by local feedbacks. Chauvin and Denvil [4] analyzed the changes of four from the 10 previously mentioned extreme indices, in the simulations of the two French models that contributed to the IPCC AR4 ensemble of simulation (CNRM-CM3 from the centre national de recherches météorologiques or CNRM and IPSL-CM4 from the institut Pierre-Simon-Laplace or IPSL). They more particularly diagnosed the sensitivity of the indices to the mean annual temperature over different wide regions. One important lesson from this analysis is that while the number of frost days varies fairly linearly with the mean temperature (except in the Mediterranean

region), the heat wave duration index increases faster than the mean temperature. This seems related to increased drying, particularly in summer that accompanies climate change over the selected regions, and amplifies the probability of occurrence of warm events. Concerning cold extremes, another feedback mentioned in the literature links snow cover and temperature through surface reflectivity change (albedo), resulting in a greater decrease in frost days occurrence near the 0°C isotherm.

Such kinds of local physical mechanisms explaining a nonlinear behavior of the climate extremes are also investigated in RCM simulations. For example, the IPCC AR4 overview some findings obtained with the PRUDENCE simulations. Among them, the study of Schär et al. [20] shows that climate change over Europe should be accompanied by an increase variability of summer temperature that they associate to an increase in the occurrence of drought conditions in response to large scale anticyclonic forcing. Other authors also mention the fact that reduced evapotranspiration in drought conditions results in an increase in surface temperature. If the same local mechanisms are present in AOGCM and RCM simulations, it is, however, difficult to evaluate if they play the same role, as they cannot be easily isolated from other processes and particularly the dynamical ones. More recently, the overview of change in the extreme events from the PRUDENCE RCM simulations by Beniston et al. [2] confirms that the intensity of extreme temperatures will likely increase more rapidly than the intensity of more moderate temperatures due to increased temperature variability. The model simulations show that by the end of this century, central Europe will experience the same number of hot days than southern Europe today. The results are robust to the choice of the RCM.

Concerning precipitation, contrary to the case of temperature, the projections of extreme events are much more sensitive to the choice of the model or the applied downscaling methodology if any. As for temperature (see above), the trends in AOGCM climate change simulations are only weakly dependent on the emission scenario for the next decades. But, in the second half of this century, if the trends appear highly dependent on the emission scenario, the intermodel and interannual variability dominates [15,23]. In addition, the increase on the indices associated to the increase in precipitation intensity is significant and consistent. These trends are even greater than the trends of mean precipitation due to a specific sensitivity of extremes to the moisture content of the atmosphere that increases nonlinearly with temperature [15]. On the contrary, the increasing trends

of indices associated to dry periods are weaker and less consistent. The geographical variation of these last indices includes some regions of decrease and the results are model-dependent. This is illustrated in Fig. 1 where we have reported the change of the maximum number of consecutive dry days in summer simulated by six of the models that participated to the IPCC AR4 ensemble of simulations. The changes appear to be fairly consistent between the models over the Mediterranean area with an increase in the length of the longest period with very low precipitation (the criteria being precipitation lower than 1 mm/day) albeit a significant variability of the amplitude. The picture is singularly different in other regions, like the Sahelian zone, where some models exhibit an increase while others project a decrease.
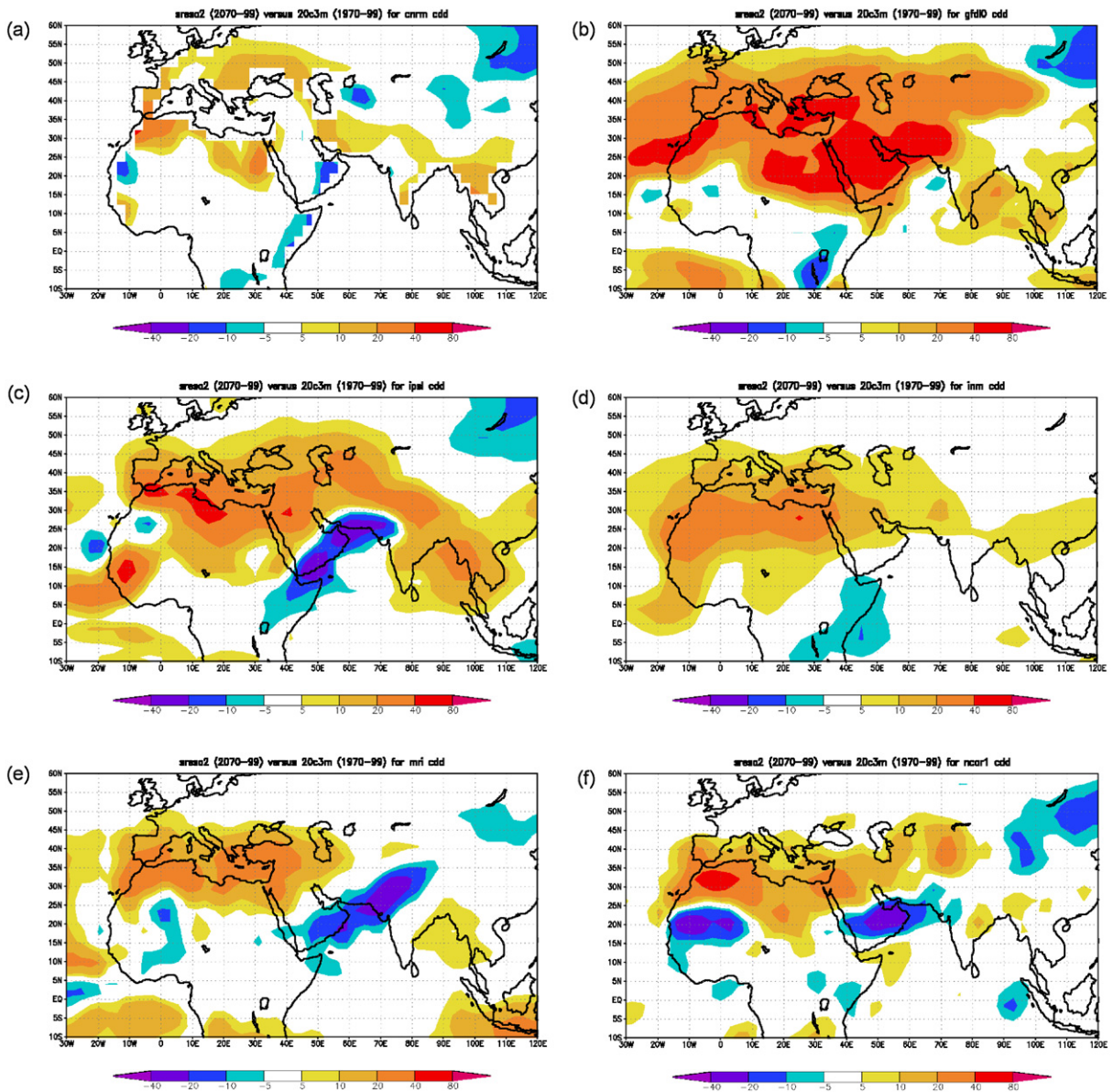

Fig. 1. Change in the maximum number of consecutive dry days – with precipitation lower than 1 mm – over Eurasia and Africa between 2070–2099 and 1970–1999, simulated by six AOGCM for the SRES A2 emission scenario: CNRM (a), GFDL (b), IPSL (c), INM (d), MRI (e), NCAR1 (f). Color classes boundaries are: -40, -20, -10, -5, 5, 10, 20, 40 and 80 days.

Changement du nombre de jours secs consécutifs – avec précipitations inférieures à 1 mm – en Eurasie et Afrique entre 2070–2099 et 1970–1999, simulé par six modèles de circulation générale couplés océan–atmosphère, suivant le scénario d'émission A2 : CNRM (a), GFDL (b), IPSL (c), INM (d), MRI (e), NCAR1 (f). Les limites des classes de couleur sont : -40, -20, -10, -5, 5, 10, 20, 40 et 80 jours.
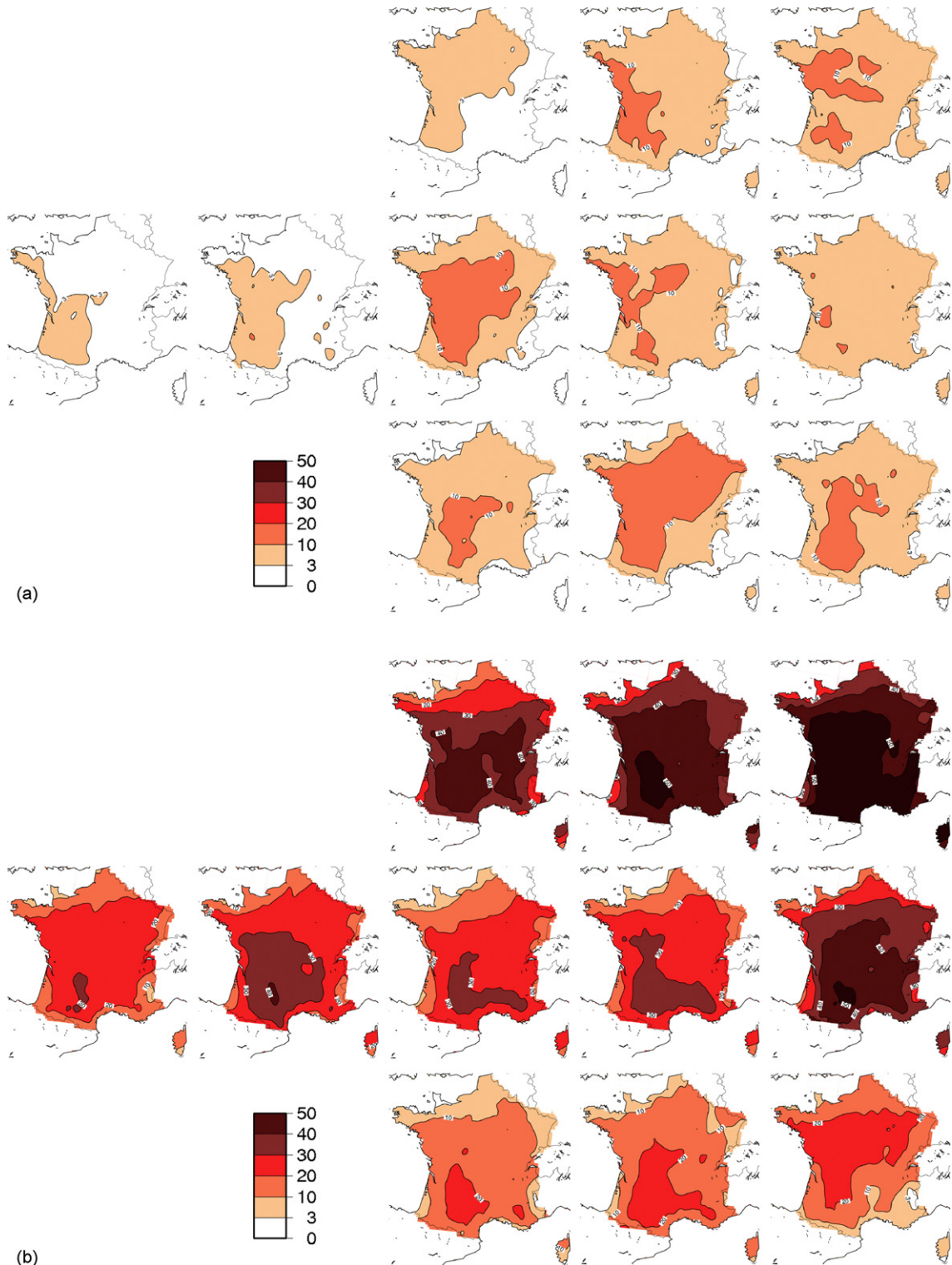
Fig. 2. Change in mean heat wave duration (number of days per period where, in interval of at least six consecutive days, the temperature passes beyond the 1960–1989 mean of a five days window centered on the same calendar day by more than 5°C) between the decadal periods of 21st century and the 1960–1989 period, simulated with the regional version of ARPEGE-Climat climate model. The lines correspond to the three SRES emission scenarios: A2 (top), A1B (middle), B1 (bottom) - and the columns to five decades – period 2001–2050 (a) and period 2051–2100 (b).

When downscaling methodologies are applied, the results on some extreme precipitation change may differ among them, even if the downscaled extremes are calculated from the same GCM outputs. This is the case in the Frei et al. [12] study comparing the simulated summer precipitation extremes of six different RCM constrained at their boundaries by the same atmospheric GCM. In particular the five-year return value of daily precipitation intensity either increases or decreases on average over central Europe, with a wide range of change between models (from −13 to +21%). The models show better consistency for the other seasons and particularly in winter. Schmidli et al. [21], who applied a combination of RCM and statistical down-scaling over Europe, also conclude that the contribution of the downscaling method is relatively small in winter but very significant in summer. This higher uncertainty in summer is explained by Frei et al. as a consequence of the representation of physical processes by the RCM. Another singularity of the projected change of precipitation in summer over Europe is that, even if the mean precipitation is expected to decrease due to a decrease in the number of wet days, extreme precipitation events might increase in some region like in central Europe [2,5,12,15]. This behavior is inter-preted by Frei et al. as a consequence of a change in the tail of the precipitation PDF but the physical nature of this change is unknown.

Other kinds of extremes have also been analyzed and synthesized in the IPCC AR4. The case of tropical cyclones is the subject of another paper in this issue by André et al. [1] and is thus not considered here. As far as extratropical storms are concerned, the most recent results tend to confirm previous findings concerning the regional character of the expected change. There is now a greater convergence of analysis showing a poleward displacement of midlatitude storm-track activity, particularly in the southern hemisphere. Whether this mean change will be accompanied with an increase risk of high wind speed over the regions experiencing an increase in storm activity is not straightforward. Several studies conclude in a reduction of the total number of storms over northern Atlantic with a corresponding increased frequency of the most intense ones and thus of the associated high winds. Over the Mediterranean Sea, the projections generally suggest a decrease in the total number of cyclones but there is no agreement on the

number of the more intense ones. Over Europe, the analysis of the PRUDENCE RCM simulations [2] shows that we might expect an increase in the frequency of the 90th percentile of wind speed for a latitude band extending roughly from 45°N to 55°N, and no change or a slight decrease further north or south. The highest changes are concentrated over the ocean, the North Sea and western Europe. However, these results have to be taken with caution, as the simulation of near surface wind speed by climate models, including RCM, remains a challenge. The wind speed variability indeed involves spatial and temporal scales that are not resolved by these models. As an alternative, statistical downscaling approaches are here of particular interest but very few were applied to diagnose climate change impact. We will give in the next section a specific example of such an application.

4. Future extreme events in France

The most part of the results reported here were obtained in the context of the above mentioned IMFREX project [9] aiming in particular at evaluating the impact of anthropogenic climate change on the temperature, precipitation and wind extremes over France. Two regional climate models based on resolution varying atmospheric GCM developed at CNRM (ARPEGE-Climat) and at IPSL/LMD (LMDz from the *Laboratoire de météorologie dynamique*) were used to simulate present (1960–1999) and future (2070–2099) climate corresponding to the so-called SRES A2 emission scenario. The resolution of the first model is of about 50 km over the Mediterranean domain and particularly over France, close to the resolutions of the RCM covering only the European domain used in the PRUDENCE project. In order to correct some bias of the models and increase the level of confidence of simulated extremes, a variable correction technique was applied to the simulated precipitation and temperature, on the basis of a direct comparison of the empirical PDF simulated by the model with observed ones [8]. As a complement, statistical downscaling methods were also applied to the model outputs. One consisted in a clustering analysis of weather regimes in the Europe-Atlantic domain [19], followed by a statistical evalua-tion of the link between a specific class and the occurrence of extremes [9]. The changes of the

Changement de la durée moyenne des vagues de chaleur (nombre de jours par périodes d'au moins six jours consécutifs, où la température dépasse d'au moins 5°C la moyenne 1960–1989 d'une fenêtre de cinq jours, centrée sur le même jour calendaire) entre les décennies du xxiᵉ siècle et la période 1960–1989, simulé par la version régionale du modèle climatique ARPEGE-Climat. Les lignes correspondent aux trois scénarios d'émission SRES : A2 (haut) , A1B (milieu), B1 (bas) – et les colonnes à cinq décades – période 2001–2050 (a) et période 2051–2100 (b).

extremes were evaluated through some of the indices proposed in the context of the STARDEX project.

The application of the above mentioned dynamical and statistical downscaling methods gives consistent results. In winter, the corrected temperature of the RCM simulations indicates an important decrease in cold days since the number of days with minimum temperature below –5°C becomes negligible at the end of this century. The cluster classification of weather regimes shows for the same season a relative decrease in the frequency of occurrence of two of the four regimes that are retained (Greenland anticyclone and blocking) while a third becomes more frequent (zonal). This also implies an important reduction of extreme cold events all over the country. Concerning intense precipitation, typically higher than 10 mm in one day, the corrected RCM precipitation exhibits an increase in the northern half that is on average over the country greater than the mean precipitation increase (typically 20 to 30% compared to around 10%). The change of the occurrence of weather regimes also favors increased winter intense precipitation events over the northern half, even if the detailed pattern of change differs from those of the two RCM. However, the applied methodologies fail at evaluating the change in the occurrence, intensity or location of very intense precipitation in southeastern France (including the so-called ''épisodes cévenols'') due to their inability to reproduce such small-scale events in present climate conditions. In summer, the corrected RCM temperatures result in consistent patterns of increase for the number of heat wave days but with different multiplicative factors ranging from roughly five to 10. The change of weather regimes (more blocking) also implies a very important increase in the risk of such events. The maximum number of consecutive dry days in summer, only inferred from the corrected RCM precipitation, is anticipated to increase by about 50% over the most part of the country, whatever the model, but with different patterns of change between the two models.

Due to the lack of long series of homogenized daily wind observations, the model outputs cannot be corrected from the model biases. The impact of climate change on the wind extremes was thus only analyzed through the statistical method previously adapted to account for more weather regimes in order to discriminate more accurately the conditions of occurrence of intense storms. Applied separately for the northern half and the southern half of the country, the risk of high wind appears to slightly increase over the north when there is no significant change over the south.

All the results that have been reported are relevant to a climate change at the end of this century compared with the present climate. To have an insight on the transient change of the extreme events occurrence or intensity change, we have reported in Fig. 2 the relative change of the number of heat waves relative to present climate, by decade and for three emission scenarios (B1, A1B and A2). The simulations are performed with a newer version of the ARPEGE-Climat model than the one used in the context of the IMFREX project, with the same resolution, but a revised physical package and another sea surface constraint (CNRM-CM3). Fig. 2 shows the change in the number of heat wave days on average over all the decades of 21st century. Only one of the three scenarios (A1B) covers the whole period while the two other simulations were limited to the periods 2020–2050 and 2070–2100. At a first glance, the simulated positive trend with the A2 emission scenario appears significantly steeper than in the above mentioned results since the multiplying factor for the three last decades compared to the observation (not shown but lower than the first simulated decade with the A1B emission scenario) is of the order of 15 rather than 10. This may be due to the model and SST forcing change that are the two major cause of uncertainties of RCM projections [10], but a contribution of internal climate variability cannot be excluded. At the scale of France and of the decade, the figure indeed shows that the number of heat wave days exhibits a strong variability. Over the first part of the century this variability is much greater than the impact of different emission scenarios since the most severe of the three (A2) produces values of the heat wave indices that are the lowest for some decades (see for example 2021–2030). It is only after the midcentury that the emission scenarios become a discriminating factor of the change since the heat wave indices follow the increase of the greenhouse gases emissions. This last is not a surprising feature since we know that due to the inertia of the climate system, at the global scale, half of the temperature trends over the next decades will be due to the commitment of accumulated emissions since the beginning of the industrial period, and that these trends will be difficult to distinguish between different scenarios over this period [15]. But it appears here with a singular acuity. In addition, the nonlinear behavior of the heat wave indices contrasts with the roughly linear change of global mean temperature. It reveals to be very sensitive to internal climate variability at the regional scale that affects western Europe. Feedback mechanism linked to physical processes associating the soil and its moisture content

to the atmosphere [4,18] might also play an important role to amplify this dependence.

5. Summary and conclusions

According to the most recent studies future climate change will be accompanied with a change in the statistics of extreme events. However, the picture is highly dependent on the type of extremes and very often the region that are considered. The level of confidence is also variable due to multiple causes of uncertainties. We have considered in this paper only relatively moderate extremes for which some standard indices have been proposed a few years ago.

The best convergence of results is found for temperature. Heat waves are expected to become longer, more intense and more frequent. The increase frequency is considered in IPCC AR4 as very likely over most land areas. The number of frost days should decrease and the growing season length increase, particularly in regions and periods when the mean temperature is close to zero like in winter over eastern Europe. Several studies point out that the change of extremes cannot be explained by a simple shift of the temperature distribution but is also associated to an increase in its variability, at least in summer. This has been related in the literature to local physical mechanisms.

Concerning precipitation extremes, the common view of the projections is that the frequency of intense events will very likely increase. Here again this change is not simply related to a shift of the precipitation distribution. Even in summer, in some regions like in central Europe, some projections show an increase in the frequency of intense precipitation events while mean precipitation is decreasing. This specific behavior is likely related to some feedback mechanisms that associate different physical processes like convection, radiation and surface fluxes, but the mechanisms at play are not well identified and may vary among models. As far as indices of dry events are concerned, the trends appear weaker and less consistent at the global scale. This reflects a strong regional dependence of the trends with convergence of results for some of them, like the increase in drought duration over the Mediterranean area, but large disagreement between model projections for other ones, like the Sahelian zone.

The changes of wind-related extremes are also regionally dependent. The agreement of many recent studies in projecting a poleward displacement of midlatitude storm tracks should impact on the pattern of change. However, it remains difficult to make the link between the large-scale circulation patterns of change and the frequency of occurrence of the most intense storms that are hardly simulated by models. The results appear often contradictory among models like over the Mediterranean Sea. However several recent studies tend to conclude that while the total number of storms might decrease, the number of the most intense ones might increase.

Some specific studies covering France show that the most likely change of extremes concerns the increase in heat waves intensity, frequency and duration, and the increase duration of drought events. The pattern of change of heavy precipitation is more uncertain but we should also expect an increase in winter, even if its amplitude is much less spectacular than for heat waves. Concerning wind extremes, the downscaling of models outputs tends to project a slight increase in higher wind speeds over the northern half of the country but a slight decrease or no change over the south.

The level of confidence on the reported results depends of course on the level of uncertainty of the methodologies that have been used to produce them. Some of these uncertainties are associated to the climate change simulations using AOGCM attributable to several causes as the choice of the emission scenario, the model (sometimes referred to as the structural uncertainty) and the internal climate variability. For the particular study of extremes that requires a downscaling step, an additional uncertainty associated to the specific downscaling methodology has to be combined with the previous ones. It appears from the few existing intercomparison of methods that, whenever the methodologies are appropriate to analyze a given climate extreme, the choice of a specific one is not the most important cause of uncertainty. For instance, dynamical downscaling and statistical downscaling often give similar results when RCM are corrected and the statistical method has a good performance on present climate conditions. Of greater concern are the two main causes of uncertainties associated to the models and to the scenarios that also dominate the uncertainty of climate change. But for extreme climate events that are regionally dependent, the uncertainty due to internal climate variability that is relatively low for the mean climate over wide regions and several decades, needs also to be considered. This is illustrated by the change of the number of heat wave days over France at the decadal time scale. A complete evaluation of the relative importance of these causes of uncertainties on the projection of climate extremes implies the construction of multimodel ensembles of simulations including different downscaling approaches. This has been done

or is currently done in the context of collaborative research projects but this effort needs to be amplified in order to reach a better characterization of the changes of extreme climate events statistics including their uncertainties.

Acknowledgments

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