Horizon 2020 Societal Challenge 5:
Climate action, environment, resource efficiency and raw materials

CONSTRAIN

CONSTRAIN: 'Constraining uncertainty of multi-decadal climate projections'

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Key messages:

- This Knowledge Gains: Summary and Implication Report (KGSIR) summarises recent advances in our understanding of the characterization and reduction of uncertainties in climate projections over the next two decades.
- Constrained estimates of temperature change confirm that the world could come close to the warming limits of the Paris Agreement Long-Term Temperature Goal over the next two decades, reinforcing the need for strong and rapid mitigation efforts.
- It is hard to rule out some of the high warming that is projected by some of the latest climate models, as these projections remain consistent with the observations when accounting for the large magnitude of internal variability in the climate system. Accounting for this variability increases the risk of higher warming over the coming decades.
- For understanding regional impacts in the near term, it is important to get internal variability right. This can be achieved by selecting simulations that show climate variability that is both relevant to the region and also in line with observations. This is particularly useful when using a large number of simulations is not possible.

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CONSTRAIN

CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

Characterising how uncertainties from scenario, policy and climate variability affect projections and climate impact studies over the next 20 to 30 years

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- It is hard to rule out some of the high warming that is projected by some of the latest climate models, as these projections remain consistent with the observations when accounting for the large magnitude of internal variability in the climate system. Accounting for this variability increases the risk of higher warming over the coming decades.
- For understanding regional impacts in the near term, it is important to get internal variability right. This can be achieved by selecting simulations that show climate variability that is both relevant to the region and also in line with observations. This is particularly useful when using a large number of simulations is not possible.

Context

Climate simulations from the Coupled Model Intercomparison Project phase 6 (CMIP6) present a very broad spectrum of possible climate evolutions over the historical and future periods. For climate projections, uncertainties can be decomposed into three contributions: (i) the internal climate variability, also called the unforced intrinsic variability of the climate system, (ii) uncertainties in the model physics resulting from unresolved processes, notably linked to the model resolution, and (iii) the range of possible external forcings, which depends on emission scenarios and natural external forcings, such as volcanic eruptions or solar variations. The relative contributions of each of these uncertainties depend on the time horizon considered, as well as on the size and location of the region of interest (Figure 1; Lehner et al., 2020).

Over the coming decades, uncertainties from internal variability and model physics are predominant in projections of annual surface temperature at either global or regional scale, with a larger contribution from model uncertainty at the global scale and overall a larger contribution from internal variability at more regional scales. The contribution of internal variability to uncertainties in projections of future global and regional temperatures may also change depending on the time horizon considered due to the influence of the external forcings. Uncertainties arising from the forcing scenarios are very small at the beginning of the temperature projections and become increasingly important over time until, around the middle of the 21st century, they become the main determinant of global surface temperature. At regional scales this is later due to a more important contribution of internal climate variability.

Understanding and reducing uncertainties in climate projections for the coming decades is of primary importance to supporting the implementation of effective adaptation and mitigation policies. We expect CMIP6 models to replace CMIP5 models in regional adaptation studies. Yet these CMIP6 models exhibit larger model uncertainties than before due to a larger range of climate sensitivity (Forster et al., 2020), as well as internal climate variability for some models (Parsons et al., 2020).

When carrying out impact studies over a particular region, it is particularly important to take these uncertainties into account, especially those associated with internal variability. Large ensembles of climate simulations from specific models are useful for exploring these uncertainties, and uncertainties in both climate sensitivity and internal variability can be reduced by constraining model results with observations. Observational constraints are usually based on the assumption that there is a reliable link between the model performance compared to the observations over the historical era and the future model behaviour.

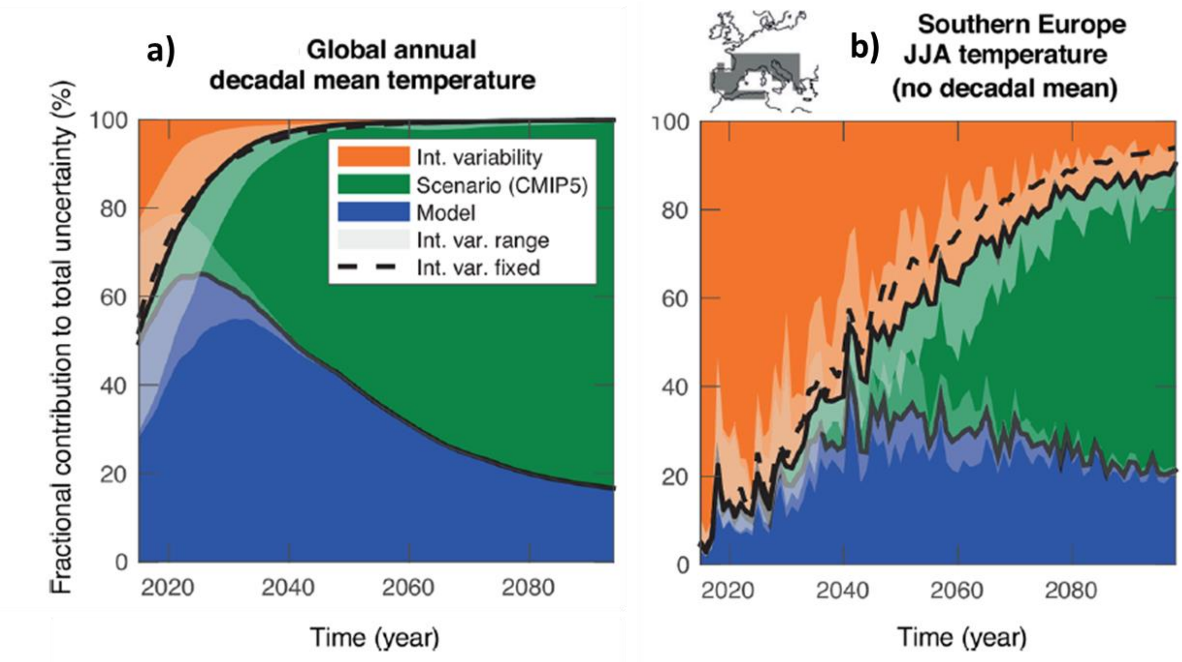

Figure 1: Relative contributions to total uncertainty from multiple single-model initial-condition large ensembles (SMILEs) for (a) global annual decadal mean temperature and (b) Southern Europe summer temperature (June-July-August). The solid black lines indicate the borders between the three sources of uncertainty: (orange) internal variability, (green) emission scenario and (blue) model. The slightly transparent white shading around those lines indicates

the uncertainty range from different SMILEs. The dashed line marks the border assuming internal variability remains fixed at its 1950-2014 multi-SMILE mean. Adapted from Lehner et al. (2020).

Summary of knowledge gains

Constraining near-term temperature projections

In order to reduce uncertainties in CMIP6 climate projections, emergent relationships between an observable quantity in a past or the present period and a quantity related to the future climate (e.g., warming level) are commonly used. These emergent relationships can be based on a physical understanding of a process driving climate feedback and rely, in that case, on available observations in order to distinguish models with a realistic representation of the process from those with a less realistic representation. They can also be based on the statistical relationship between past and future warming. In this section, we summarise and compare some of the CONSTRAIN findings using near-term Global Surface Air Temperature (GSAT) change as an example.

In the framework of the European Climate Prediction project (EUCP), Brunner et al. (2020) developed a method to weight the CMIP6 models based on their performance compared to observations, as well as their independence regarding the possible shared climate model components (e.g., same oceanic model) (see Abramowitz et al, 2019 for a review of the model dependence multi-model climate ensemble). More recently, Ribes et al. (2021) developed a statistical method to constrain the GSAT forced response using climate models to provide an estimation of the forced response and the observations to obtain a posterior (i.e., constrained) distribution.

In addition to the CMIP6 climate models, climate model emulators have been widely used in the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) due to their ability to perform a very large number of simulations faster and at lower calculation costs than more complex Earth system models. Therefore, they can be run many times (e.g. one thousand times) for a single emission scenario with different values of their parameters (e.g., the response of carbon sinks to global warming). This makes it possible to span the range of uncertainties for future climate projections. As not all the parameter combinations produce realistic climate projections, the model outputs are constrained using observations of historical climate change. For instance, Quilcaille et al. (2022) uses the observed GSAT change over recent decades, compatible CO_2 fossil fuel emissions and historical cumulative net ocean CO_2 sink to constrain the outputs from the OSCAR v3.1 climate model emulator (Gasser et al., 2017).

The three methods are summarised in Table 1 and Figure 2 summarises the change in GSAT average over the 2021-2031 and 2031-2041 decades relative to the 1850-1900 pre-industrial period with and without constraints from these three different methods. For both periods, there are differences in the unconstrained temperature changes between the three methods, with lower temperature changes using OSCAR than those based directly on the CMIP6 models. This difference seems to be due to the fact that OSCAR is still calibrated with the previous climate model generation (CMIP5), which is characterised by a lower warming on average in comparison to CMIP6. The other two methods, which are both based on CMIP6, show relatively close unconstrained mean temperature changes but have more important differences in the range of uncertainty. These differences stem from different subsets of CMIP6 models used, as well as the processing and statistics used. In order to put these results in perspective, the 1.5°C and 2°C warming levels defined as anthropogenic warming (i.e. with the internal variability filtered out) are also highlighted in Figure 2. This definition is consistent with the results of the methods from Ribes et al. (2021) and Quilcaille et al. (2022). The results from Brunner et al. (2020), however, still contain internal climate variability. Therefore the temperature changes from this method are not directly comparable to these warming levels.

The temperature changes are evaluated for several Shared Socioeconomic Pathways (SSPs) intending to span the range of plausible futures. These scenarios are based on different narratives describing the major socio-economic trends that could shape future society, ranging from SSP1, the most sustainable, to SSP5, based on fossil-fueled development. Each of these baseline SSP scenarios are combined with mitigation targets that are expressed as the level to which radiative forcing is limited in 2100, and which range from 1.9 to 8.5 $W.m^{-2}$. In this report, the scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 are used to evaluate the constrained and unconstrained temperature changes for the several methods. Note that the scenario SSP1-1.9 was not available for the method from Brunner et al. (2020).

Over the next decade (2021-2031), the 90% confidence ranges from the projections from Ribes et al. (2021) indicate that GSAT averaged over that decade could exceed 1.5°C for the SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios, although a large proportion of values remain below the 1.5°C threshold, notably with the SSP1-2.6 scenario. Only in the very low emissions scenarios SSP1-1.9 does the constrained temperature change from Ribes et al. (2021) not exceed 1.5°C over the course of a decade. The 90% uncertainty range of temperature change is wider with the method from Brunner et al. (2020) as internal climate variability is still included in the results. As a result, a larger part of the 90% uncertainty range for the average temperature change relative to 1850-1900 is higher than 1.5°C for the 2021-2031 decade. The constrained temperature changes from Quilcaille et al. (2022) stay below the 1.5°C threshold for any scenario. These low values in comparison to the other methods are induced by the lower unconstrained temperature change related to the calibration with CMIP5, but also by the weighting approach of the ensemble simulations, which gives a lot of weight to a very small number of members. Further work can improve the application of constraints on the output of the OSCAR model.

Constraint method	Model	Observations
Brunner et al. (2020)	CMIP6 multi-model ensemble	Climate model weighting by independence and performance (ClimWIP) method (e.g., Knutti et al., 2017b; Brunner et al., 2019)
Ribes et al. (2021)	CMIP6 multi-model ensemble	GSAT over the whole historical period
Quilcaille et al. (2022)	OSCAR v3.1	GSAT over the recent decades; Compatible CO2 fossil fuel emissions; Historical cumulative net ocean CO2 sink

Table 1: Summary of the three constraint methods used to constrain the global mean air-surface temperature (GSAT) projections in Figure 2, with the reference, the model or multi-model ensemble used and the observations used as constraint.

The average GSAT level over the decade 2031-2041 could exceed 1.5°C when considering the 90% range of constrained temperatures from Ribes et al. (2021) for the very low emission scenario SSP1-1.9. A large proportion of the constrained temperature uncertainty range is higher than 1.5°C for the other scenarios, which highlights the high risk of exceeding this warming level before the middle of the 21st century if no deep emissions reductions are achieved globally over the next decade. Only a small part of the constrained temperature 90% range is above 2°C for Ribes et al. (2021) considering the SSP5-8.5 scenario. Considering the method from Brunner et al. (2020), a very small part of the 90% uncertainty range of the constrained temperature change has a temperature higher than 2°C over the decade 2031-2041 in comparison to the 1850-1900 period for the SSP1-2.6 and SSP2-4.5 scenario, which becomes larger for the SSP3-7.0 and SSP5-8.5 scenario. As the results of this method contain internal climate variability, the 90% range is larger than the one from Ribes et al. (2021). More than half of the 90% uncertainty range of the constrained temperature change has a temperature higher than 1.5°C for the four SSPs scenario used with the Brunner et al. (2020) method. As for the 2021-2031 decade, the 90% range constrained temperature changes from Quilcaille et al. (2022) are well below the other methods, but still cannot exclude the possibility that 1.5°C of global warming is crossed when global emissions follow SSP2-4.5, SSP3-7.0 or SSP5-8.5.

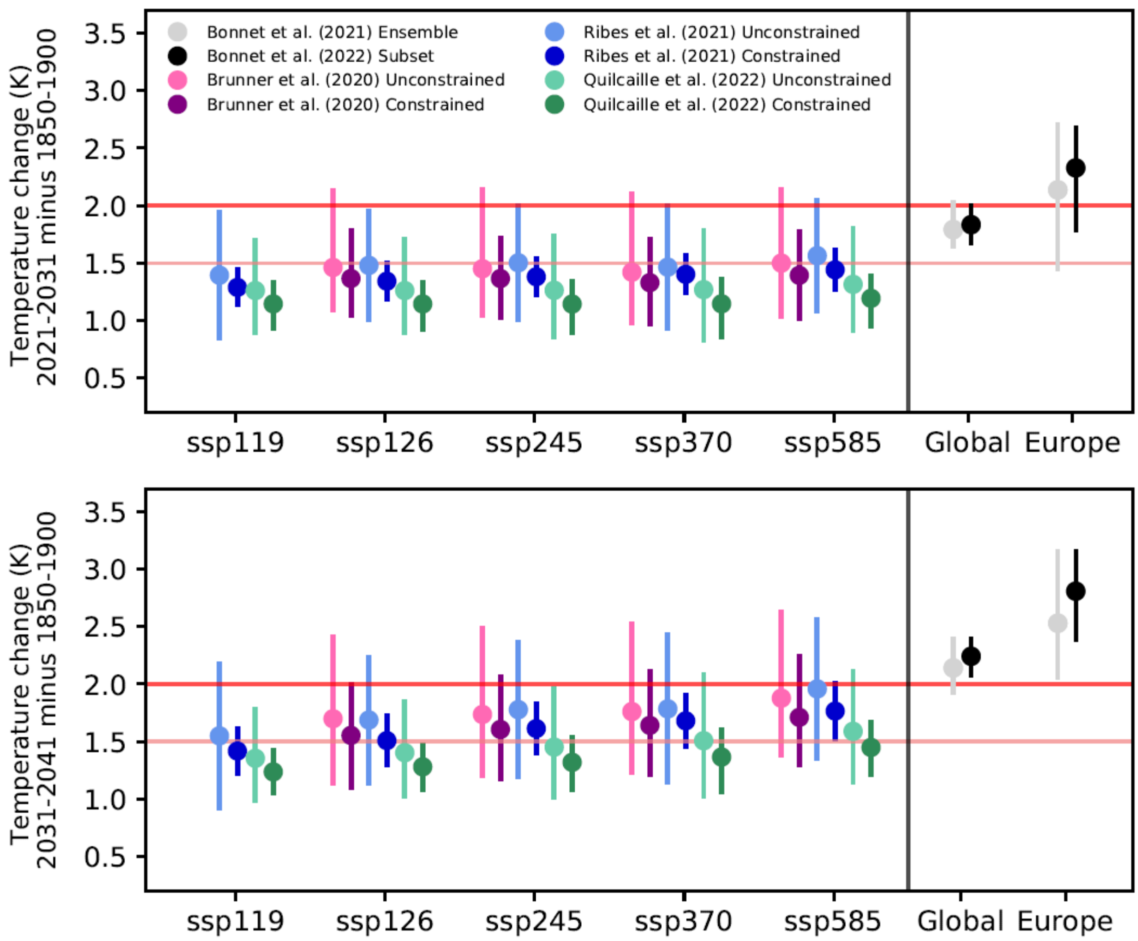

Figure 2: Unconstrained and constrained average (dots) and 5-95% range (bars) global surface temperature changes calculated over the 2021-2031 (upper), 2031-2041 (bottom) periods relative to 1850-1900 for different Shared Socioeconomic Pathways (SSPs) scenarios from two methods based on the CMIP6 latest climate models generation (Brunner et al., 2020 and Ribes et al., 2021) and one method based on the OSCAR climate emulator (Quilcaille et al., 2022). Temperature changes from the IPSL ensemble of climate simulations (Bonnet et al., 2021a, in grey) and for a subset of members selected according to their consistency with AMOC and GSAT trends (Bonnet et al., 2021b, in black) over the globe and over Europe, with

the average changes (dots) and the minimum and maximum (bars). The 1.5°C and 2°C warming levels are highlighted with the light red and red lines.

Overall, several methods to estimate and reduce the uncertainties related to the projected change in global mean surface temperature have been developed within the CONSTRAIN project framework. Although there are some differences between the methods, the results confirm that without strong and rapid mitigation, the world will increasingly approach the 2°C warming level in the coming decades.

Risk related to the internal climate variability over the next decades

Some CMIP6 models are characterised by a larger low-frequency internal climate variability than their CMIP5 counterparts (Parsons et al., 2020). Such low-frequency internal variability at decadal to multi-centennial timescales can temporarily enhance or reduce the long-term imprints of externally forced climate change. It also has implications for the way climate models should be compared to observations.

Using an ensemble of simulations from one specific CMIP6 climate model (IPSL-CM6A-LR; Boucher et al., 2020; Bonnet et al., 2021a), which has a relatively high internal low frequency variability within the CMIP6 multimodel ensemble, and using the intermediate emissions scenario SSP245, Bonnet et al., (2021b) provide new insights about the risk of a larger warming due to the low-frequency internal climate variability over the next decades. A strong positive relationship exists between the GSAT and the Atlantic Meridional Overturning Circulation (AMOC) trends since the 1940s. The ensemble members with the smallest rates of global warming since the 1940s, consistent with the observed trend, are also those with a large weakening of the AMOC, which is consistent with a recent reconstruction from Caesar et al. (2018). Based on these results, a subset of members most consistent in terms of warming trends and AMOC weakening, as well as in the temperature evolution since the 1900s is selected. This subset of ensemble members also matches several AMOC observational fingerprints, which are in line with such a weakening. Together, these results suggest that internal variability from the Atlantic Ocean may have dampened the magnitude of global warming over the historical era.

The risk related to this low-frequency internal variability is then analysed by looking at the future near-term evolution of this subset of members. Over the next few decades, there is on average a smaller AMOC weakening in the subset of members in comparison to the rest of the IPSL ensemble. This is associated with a larger warming rate of about 0.43 K per decade on average over the 2021-2041 period for the subset of ensemble members in comparison to the IPSL ensemble mean of 0.35 K per decade. In comparison, the warming rate over the 2000-2020 period is of 0.29 K per decade for the IPSL ensemble mean and of 0.27 K per decade for the subset of members on average. The influence of this internal variability is however limited, as both the AMOC and GSAT low-frequency internal variability are projected to decrease in response to external forcings.

Considering the 2021-2031 and 2031-2041 decades, the uncertainty related to the GSAT internal climate variability is found to be almost as large as the constrained temperature range from Ribes et al. (2021) (Figure 2). As expected from unconstrained climate simulations from a model with a relatively large climate sensitivity (Shlund et al., 2020), this ensemble of climate simulations shows a much larger warming than that of the constrained temperature from the three different methods. This result highlights the risk associated with low-frequency internal climate variability, which may induce faster temperature increases over the coming decades than anthropogenic warming only. As a result, global mean surface temperature could exceed 2°C over the next decades because of the low-frequency internal climate variability, inducing higher risks related to climate impacts, while a 2°C warming level (i.e. the anthropogenic warming without internal variability) would not be exceeded.

Although the realism of this high internal variability needs to be evaluated, these results reinforce the risk of a higher rate in the increase of global surface temperatures over the next decades induced by the low-frequency internal variability of the climate system. In a broader context, this work also provides a useful framework for evaluating the contribution of internal climate variability to future changes by selecting a subset of members based on their consistency to the variable of interest. Such a method could be applied in climate impact studies.

Uncertainties in impact studies

As stated in the introduction, uncertainty in GSAT change related to the internal climate variability is very large at regional scales, over Europe for example, in comparison to the global scale (Figure 2). In addition, temperature change at regional scale could be higher than at global scale (Figure 2). Taking the IPSL ensemble as an example, the uncertainty is larger than the unconstrained temperature from the three methods analysed before. It is therefore important to assess and take into account the impact of uncertainties related to internal variability in impact studies.

In order to assess the impact of climate change on environment and resources, as well as to provide appropriate adaptation policies, Global Climate model (GCM) or Regional Climate model (RCM) are usually used as input to impact models. However, biases (i.e. discrepancies from the observations) are often present in climate models (Christensen et al., 2008), which could lead to a misrepresentation of the statistical distribution of the simulated variables and lead to meaningless results for the related climate impact study (Addor et al., 2016; Vrac et al., 2016). To overcome this issue, climate simulations are often adjusted using bias adjustment methods before their use in climate impact models. There are a variety of methods for this, depending on the variable and the region of interest (a review is provided in the IPCC AR6 WGI, chapter 10, Doblas-Reyes et al., 2021).

When applying a bias correction prior to an impact study, a reference period on which the correction is calibrated is chosen. This period generally corresponds to the last 20 or 30 years, which often has good observational conditions. However, these timescales can be largely influenced by the internal climate variability, especially at the multidecadal and multi-centennial timescales. Over Europe for example, the Atlantic Multidecadal Variability (AMV, Knight et al., 2006), which is the leading mode of the low-frequency internal climate variability in the North Atlantic, is known to influence the European climate at multidecadal timescale.

To evaluate the impact of the internal climate variability in the bias adjustment results, a new pseudo-reality framework has been developed in Bonnet et al. (2022) based on the IPSL CMIP6 ensemble of climate simulations. A pseudo-reality framework consists of successively choosing a simulation as a reference to estimate the biases with respect to the other simulations. The idea of this new framework is to use two simulations with opposite AMV phases over the reference period as pseudo-realities and to use them to calibrate a bias adjustment for two simulations also characterised by opposite AMV phases (Figure 3a). The member with a positive AMV phase is characterised by higher surface temperature over Europe in comparison to the member with a negative AMV phase (Figure 3b). New indices have been developed in order to quantify how the internal climate variability could influence the mean and extreme surface temperatures bias adjustment results over the near-future (i.e., over the 2029-2059 period). The value of this method is that it is easily reusable over another region or with another bias adjustment method. In particular, this could allow a quick comparison of the influence of internal variability on the outcome of different adjustment methods without having to apply it to an entire simulation ensemble.

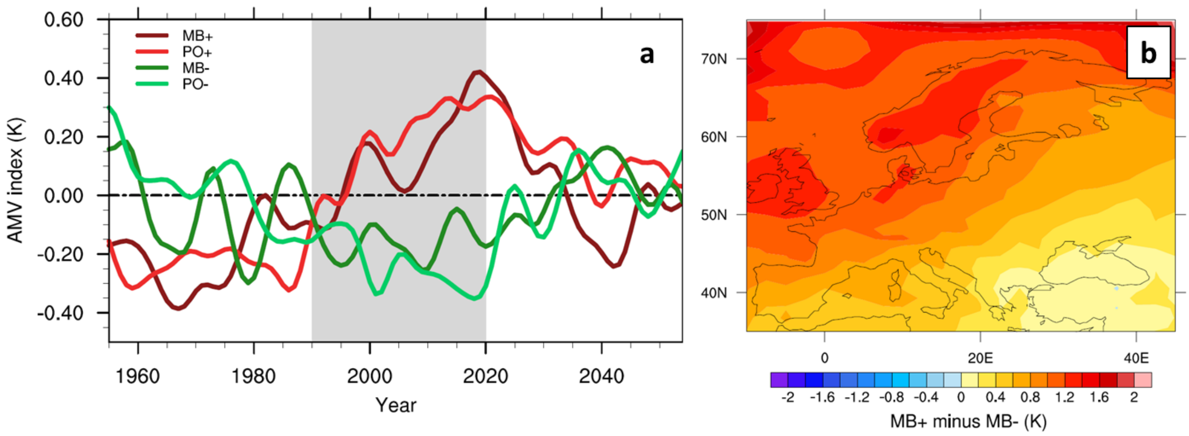

Figure 3: (a) Evolution of the Atlantic Multidecadal Variability (AMV) index of the four members of interest from the IPSL ensemble, with MB the members to be bias-adjusted and PO the pseudo-observations. The AMV index is defined as the average North Atlantic Sea Surface Temperature (SST) with the forced signal removed (i.e. estimated by the ensemble mean of the IPSL ensemble and removed for each member). In gray, the reference period used for the bias adjustment method. (b) Difference in Surface temperature (K) between the members #16 and #25 of the IPSL ensemble to be bias-adjusted over the study area.

The results show that the results in mean and extreme surface temperature of the bias-adjusted simulations are characterised by larger biases in the future (2029-2059 period) when the simulations are bias-adjusted with a simulation in an opposite phase of the low-frequency internal climate variability (here the AMV) than with a simulation in a same phase. Therefore, bias adjusting climate model simulations to observations with modes of variability that are out of phase in the reference period may lead to undesired biases in future projections. These results bring out the importance of generating a large ensemble of climate simulations and selecting simulations with modes of climate variability in phase with observations before conducting a bias-adjustment method when the bias adjustment of a whole ensemble is not possible. Such a selection has to be targeted to the mode(s) of variability that are relevant to the region of interest and may depend on the climate impacts being considered. Another way could be to perform a bias adjustment method using a longer (i.e. > 30 years) reference period, as previously suggested (Chen et al., 2020), so as to minimise the impact of low-frequency internal climate variability.

Implications

- Different methods lead to slightly different projected constrained temperatures, but there is agreement that global temperature changes will be close to 2°C in the coming decades unless strong mitigation efforts are implemented that potentially keep warming well below 2°C and pursue to limit it to 1.5°C as required by the Paris Agreement.

- Some models remain consistent with the observations, despite a larger than average warming in comparison to the observations, because they exhibit a large amount of internal variability. Accounting for this reinforces the risk of a higher warming over the coming decades. Emerging constraint approaches that try to constrain future warming using recent decades should therefore fully embrace the issue of low-frequency internal variability and take into account individual ensemble members rather than ensemble means, as this might have crucial implications in terms of how different models are weighted in such studies.

- A new method has been developed in the context of the CONSTRAIN method to assess the impact of low-frequency internal climate variability on the results of a bias adjustment method for impact studies. This method is easily reusable over other regions or with other bias adjustment methods.

- Large ensembles of climate simulations are useful tools for assessing the influence of internal climate variability in impact studies. A selection of simulations with modes of climate variability in phase with observations is preferable before conducting a bias-adjustment method. Such a selection has to be targeted to the mode(s) of variability that are relevant to the region of interest and may depend on the climate impacts being considered. Alternatively the bias adjustment method could be performed by using a longer (i.e. > 30 years) reference period to minimise the impact of low-frequency internal climate variability in climate impact studies.

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