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Emergence of climate change signals in marine ecosystem thermal niches

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Temperature is one of the most important drivers of global ocean patterns of biodiversity\(^1,2,3\), shaping thermal niches through thresholds of physiological thermal tolerance\(^4\). Because of anthropogenic global warming, lower and upper thermal niche bounds are predicted to change affecting the future distribution of marine species\(^5,6\). Current working hypotheses suggest an expansion of ectotherms toward their poleward boundaries\(^7,8\). Nonetheless, the knowledge of the timing and extent of these rearrangements across latitude and depth remains limited. Here, using daily data across the water column from both Ocean Sites network observations and novel Earth System Model, we track the emergence of thermal niches whose lower bound is warmer than their current upper bound, potentially disrupting marine habitats. We show that these developments will emerge by ~2030 in subsurface waters (~50 – 1000 m) if anthropogenic emissions continue to rise, whereas they delay several decades if emissions are substantially reduced. By 2100, thermal niches will be warmer than current counterparts. However, we further show that depending on the vertical level, concomitant changes in both boundaries will result in wider or narrower thermal niches. These results suggest that the redistribution of marine species might differ across depth, shedding light upon a much more complex picture of the impact of climate change on marine habitats.

Anthropogenic climate change fingerprints in the world’s oceans by warming significantly their upper layers\(^9,10\). This increase in heat content is projected to alter long-term well defined thermal niches driving species redistribution at a global scale\(^11,12\). These changes are already affecting goods and services provided by the oceans\(^13\), and are projected to be amplified with rising greenhouse gases emissions. A close coupling between marine organisms’ physiological thermal tolerances and environmental temperature\(^14,15\) suggests that distributional shifts can be predicted by tracking changes on the lower and upper bounds of the ecosystems’ thermal niches\(^6\). Few studies have yet considered the vertical structure of temperature in the ocean (e.g., ref. 16), thus current understanding on how and when climate change will drive changes in marine habitats is restricted to the ocean surface (e.g., ref. 12,17,18). However, the surface is
just the tip of the iceberg of an ocean at change under anthropogenic pressure, and the general
extent to which species distribution will be affected by changes in ecosystems’ thermal niches
below the surface remains an open question.

Predicting changes in the distribution of marine ecosystems due to variations in environmental
temperature relies on the assumption that species’ tolerance ranges reflect the magnitude of the
local temperature variability\textsuperscript{15,19}. Marine organisms tend to occupy the extension at which
environmental temperatures lie within their tolerances\textsuperscript{20}, perhaps owing to oxygen limitation of
these tolerance ranges\textsuperscript{21}. We thus consider the lower and upper limits of the thermal niches to
be represented by the environmental temperature minimum (Tmin) and maximum (Tmax). At
each depth, Tmin and Tmax correspond to the annual 1\textsuperscript{st} and 99\textsuperscript{th} percentile as computed using
the statistical distribution of daily records, respectively. Though this approach encompasses
most of the range of temperature variability, it can yield conservative projections as tolerance
ranges can be wider than environmental thermal niches\textsuperscript{22,23}, and as ectotherms display some
plasticity to adapt to environmental temperatures that challenge their tolerance limits\textsuperscript{24,25}.
Nonetheless, there is limited capacity of acclimation when long-term heating occurs\textsuperscript{26}, especially
for tropical species\textsuperscript{27} and during reproductive stages\textsuperscript{28}. In this regard, our overarching objective
is to understand how and when global warming-induced changes in thermal niches over the
water column will take place in the future affecting current marine ecosystems.

We take advantage of comprehensive data sets of daily three-dimensional ocean temperatures
from both the long-term Ocean Sites (OS) network and a state-of-the-art Earth System Model
(ESM). This novel data set and its exploitation represents a major novelty to improve our
understanding of how future climate change will impact marine ecosystems. To provide a
reliable framework upon which to derive the future evolution of lower and upper thermal niche
bounds, we select six OS stations for which at least seven years of daily temperature
observations from the surface to ~1000 m depth are available (Table S1). We map them into
polar, temperate, and tropical ocean domains, and determine the surface area of ocean
domains informed by the OS stations by computing the level of similarity in daily temperature
profiles using a p-value analysis (Fig. 1a, see Methods). A pattern of alternation of cooling and
warming periods is seen over the time of available observations (Fig. 1b). In general, these
episodes last a few years though they last longer at the northernmost stations. Though
measurements’ coverage is not complete along depth and time for some stations, we consider
they allow us to confidently compute annual Tmin and Tmax, and extract trends to compare with the ESM simulation (see Supplementary Material).

Three-members ensemble simulations were performed with CNRM-ESM2-1\(^{29}\) (see Methods) encompassing the historical period (1850-2014) followed by two future projections (2015-2100) that explore very contrasted emission pathways\(^{30}\) developed for the sixth Coupled Model Intercomparison Project\(^{31}\) (CMIP6); a low (SSP1-2.6) and a high (SSP5-8.5) emission pathways. To overlap observations with the model, observations were daily resampled, and remapped into the simulation’s vertical levels. At each OS location, we extract a subsample of the historical + SSP5-8.5 simulation that matches the period of the observations. Comparison between both data sets (Fig. S1) show simulation deviates from observations at the northernmost stations, especially at station FRAM at which observations show a warming period before 2010 that can be originated from an anomaly advection of North Atlantic waters northwards\(^{32}\). This anomalous episode can also be behind the positive anomaly at station CIS-1.
Figure 1: Overview and geophysical properties of the six long-term Ocean Sites (OS) stations. (a) Map illustrating the geographic location and period of the six available long-term OS stations. Colour code indicates how the OS stations are grouped into polar (blue), temperate (green) and tropical (orange) ocean domains according to their geographical coordinates. The shading indicates the ocean domains that are informed by each OS station. These domains are determined by assessing the level of similarity between daily profiles using a statistical p-value analysis (see Methods). (b) Depth-time hovmoller plots of daily ocean temperature anomalies from the surface to 1000 m. Anomalies are computed from the full observational records by removing the daily climatological temperature to daily temperature. Red (blue) colours indicate warmer (cooler) daily temperature variations with respect to the daily climatological temperature.

Observations and model data are then used to compute profiles of Tmin and Tmax over the available period. We derive the anomalies of the lower and upper thermal range boundaries by removing the mean temperature profile from Tmin and Tmax profiles. These profiles are then employed to determine the magnitude of the thermal range across depth (Fig. 2), informing of the vertical structure of current ecosystems’ thermal niches. As expected, thermal ranges decrease toward high and low latitudes being wider at temperate domains, and toward deeper layers as temperature variability does. The largest amplitude of the thermal range takes place in the first 200 m of the water column where most of the biota lives. This sheds light on a more complex picture of the temperature profiles, which have been overlooked by previous studies (e.g., ref. 17, 18).
Figure 2: Vertical profiles of thermal range boundaries and associated thermal niches at each OS station. Vertical profiles of the lower and upper boundaries of the thermal range are presented here with anomalies of Tmin (1st percentile, bluish colours) and Tmax (99th percentile, reddish colours) relative to temperature mean over the period of available observations, respectively. Vertical profiles are given between the surface to 1000 m depth. They are indicated for both observations (shading), and model (solid lines). Model profiles are represented with (bold lines) and without (thin lines) applying the observational mask in space and time. Dashed horizontal lines demarcate the water column into upper epipelagic (surface – 50 m), lower epipelagic (50 – 200 m) and mesopelagic (200 – 1000 m) layers. Subplots at right show vertical profiles of the thermal niches defined by their thermal midpoint (arithmetic mean of Tmin and Tmax; solid line) and thermal breadth ([Tmax – Tmin]; shading). Thermal niches as derived from OS observations are given in orange, while those derived from the model are given in grey.

Thermal niches can be represented by a combination of their breadth and their midpoint (Fig. 2, right panels). Thermal breadth corresponds to the difference between Tmin and Tmax. Midpoint
temperature (Tmidpoint) is computed as the arithmetic mean of Tmin and Tmax. The shape of thermal niches is mostly symmetric with a wider breadth above 50 m that narrows rapidly with depth. Modelled thermal niches (in grey) are in agreement with observed counterparts (in orange), except for an underestimation at station FRAM. Excluding station FRAM, the agreement is further corroborated by Tmidpoint profiles (R² > 0.8). At MBARI, simulated thermal ranges as well as the Tmidpoint profile are warmer than derived from the observations, maybe due to the difficulties of CNRM-ESM2-1 to reproduce the cold waters off the California upwelling (see ref. 29).

Emergence of changes in current thermal niches

With the shape of current thermal niches established, we track when and where concomitant changes in the lower and upper boundaries of the thermal range will take place. Concomitant changes in Tmin and Tmax can be seen as a compound event since they can result in several developments of the thermal niches, possibly leading to a redistribution of marine ecosystems or driving to their collapses (Fig. S2). Thermal niches will shift toward warming or cooling temperatures if both the temperature of the lower and upper bounds of the thermal range increases or decreases, respectively. In addition, thermal niches can also expand if Tmax warms more rapidly than Tmin, or narrow if Tmin warms more rapidly than Tmax. As depicted by the observations and as simulated by CNRM-ESM2-1, trends in Tmin and Tmax over the recent years (Fig. S3 and S4) lead to various developments in thermal niches. In general, warming trends were stronger than cooling trends thus resulting in warmer thermal niches. The pace at which these changes occurred varies between stations, but it has been shown to push marine organisms to acclimate to a warmer environment (see Supplementary Material). Overlapping to this warming, an imbalanced warming of Tmax results in wider thermal niches. These expanded thermal niches may host more marine species generating interspecific competition for resources and space. By contrast, excess warming of Tmin shrinks the thermal range, possibly leading to the loss of ecosystems' habitability. Though the responses of marine organisms to these changes can be difficult to predict, as global warming trends are likely to increase, it is key to understand the time at which these changes may occur.

To assess how and when future thermal niches may emerge from warming-induced changes in the thermal range bounds, we modify the canonical approach of the Time of Emergence (ToE). We track the evolution of Tmin across the water column under two contrasted scenarios, i.e., SSP5-8.5 and SSP1-2.6, with respect to the current (1990 to 2020
mean period) $T_{midpoint}$ and $T_{max}$, considered as key thresholds for marine ecosystems. When $T_{min}$ surpasses a first threshold ($T_{midpoint}$), we consider that the shift of the thermal range may represent a warning to current ecosystems since $T_{midpoint}$ has been observed to align well with the temperature of maximum ecological success of a specific species (see ref. 5). Furthermore, when an ecosystem will be exposed to a $T_{min}$ that is warmer than the current $T_{max}$, we consider that organisms should deal with a completely new thermal niche (see Fig. 3a).

**Figure 3:** Emergence of climate change signals in thermal ranges. (a) Schematic explaining how the evolution of the lower bound of the thermal range ($T_{min}$) may result in the emergence of changes in marine thermal niches pending on when and where $T_{min}$ is warmer than current $T_{midpoint}$ or $T_{max}$. (b) Vertical profiles of the timing of when future $T_{min}$ will be warmer than current $T_{midpoint}$ or $T_{max}$. (c)
Tmidpoint and Tmax at each OS station. Current period is considered as the average between 1990 to 2020. At each depth level, this timing is considered as the year at which a spline for the whole period simulation (1850 to 2100) time-series of Tmin surpasses a threshold based on the spline for the current period time-series of Tmidpoint (gold lines) or Tmax (dark red lines). Further details are available in the Methods section. Solid (dashed) lines represent the timing computed as simulated for SSP5-8.5 (SSP1-2.6). Dashed horizontal lines demarcate the water column into upper epipelagic (surface – 50 m), lower epipelagic (50 – 200 m) and mesopelagic (200 – 1000 m) layers.

Considering the approach discussed above, we find a rather good agreement across all OS stations in the first 200 m of the water column (Fig. 3b), with only noticeable changes in the thermal range within lower epipelagic waters (50 – 200 m). This feature results from both the shape of the current thermal ranges (Fig. 2), and the rather homogeneous warming of the ocean in these layers (see Fig. S3). The responses in mesopelagic waters (200 – 1000 m) are more contrasted. In the four northernmost stations, the emergence of these warnings delay in the deepest layers (> 700 m) as the rate of change of Tmin decreases. At BATS station, at which Tmin and Tmidpoint are close across the mesopelagic layer, Tmin crosses this threshold as early as the present decade. Small rates of change in the thermal ranges preclude this warning to emerge during this century at the mesopelagic layer of HOT (see Figure S5), though they appear by ~2040 below 700 m depth as Tmin warms more rapidly.

The emergence of Tmin crossing current Tmax follows a similar profile of that for Tmidpoint, but with a delay of about two to four decades. Still, it comes up above 200 m depth before 2080 in all domains. Below 200 m, it emerges before 2070 following a high emission pathway, appearing sooner in the tropics than in northern stations. Consistently across all stations, emergence times are delayed by several decades when a low emission pathway is considered (dashed lines).

End-of-the-century thermal niches

We now focus on the changes in thermal ranges by the end of the century (2080 – 2100). This analysis is relevant for tracking the impact of climate change on marine ecosystems as the lower and the upper boundaries of the thermal range will continue to change even after crossing ecosystems thresholds. As changes in thermal range boundaries can take place in both directions and at different pace because of physical and dynamical ocean processes, they can result in complex rearrangements of the thermal niches by the end of the century.

Under the high emission scenario, end-of-the-century thermal niches differ from those estimated over the historical period (1990 – 2014) (Fig. 4 and S6). In general, both the lower and upper
bounds of the thermal niches will be warmer (red shading) across the water column. Situations in which end-of-century Tmin will be warmer than historical Tmax occur at all stations within either the epi- or mesopelagic, or in both layers, in agreement with emergence times shown in Fig. 3. The only exceptions are found in the deepest levels of the station FRAM, and in most parts of the mesopelagic layer of the station HOT-01, where Tmax and Tmin are predicted to be slightly cooler than the historical period. Such features may result from seasonal changes in deep water mass flow or in subtropical cells, redistributing heat across ocean layers.

Figure 4: End-of-the-century thermal ranges resulting from concomitant changes in their lower and upper bounds in response to climate change. Vertical profiles illustrate temperature anomalies for Tmin and Tmax with respect to the mean over last years of the historical simulation (taken as the 1990 to 2014 average) for the historical (1990 – 2014; light lines) and end-of-the-century (2080 – 2100) periods. Vertical profiles for the future period are only given for the high emission scenario (SSP5-8.5). Reddish (bluish) shading areas indicate ocean layers where the lower (Tmin) and the upper (Tmax) boundaries of the end-of-the-century thermal range are warmer (cooler) than the current period. Dashed horizontal lines demarcate the water column into upper epipelagic (surface – 50 m), lower epipelagic (50 – 200 m) and mesopelagic (200 – 1000 m) domains. Right-hand sided boxes
indicate how the resulting changes in both boundaries have reshaped the vertical structure of the thermal ranges. Shrinking of the
thermal range will result if Tmin increases and Tmax either decreases or increases slower. Expanding of the thermal range will
result if Tmax increases and Tmin either decrease or increase slower. A warmer (cooler) thermal range will result if both Tmin and
Tmax increases (decreases) at comparable paces. All changes are rounded to 0.05°C consistent with estimates of the internal
climate variability of the thermal range across the water column. Boxes are given for both high emission (SSP5-8.5) and low
emission (SSP1-2.6) scenarios.

Consequently to these changes, complex thermal niche developments take place (Fig. 4). Depending on the station and the layer considered, end-of-the-century thermal niches will be
warmer and narrower as a result of a quicker warming of Tmin (yellow rectangles), or warmer
and wider as Tmax warms more rapidly than Tmin (violet rectangles). In the former case, new
conditions will challenge local adaptation of inhabitant organisms. In the latter, possible spread
of species from neighbour habitats may generate additional stresses by changing species
interaction. Wider thermal niches will result above 200 m at all stations under a high-emission
scenario with the only exception at station CIS-1 due to an excess warming of Tmin (Fig. S6a).
Below 200 m, the pace of warming of both bounds are comparable, generating both wide or
narrow thermal niches depending on the station. Considering a low emission scenario, more
heterogeneous developments appear. All stations show warming anomalies (Fig. S6b), except
at station CIS-1 where both bounds will generally be cooler than the historical mean. Only
developments at stations FRAM and K276 are consistent across emission scenarios.

Concluding remarks

Marine ecosystems are already being threatened by numbers of anthropogenic stressors like
fishing, acoustic pollution or plastics. Climate change exacerbates their degradation by
pushing organisms to adapt to a less-oxygen warmer ocean. In addition, extreme events like
marine heatwaves are expected to increase as a consequence of global warming with
devastating effects on marine ecosystems. Because of these climatic impact drivers, the current
working hypotheses suggest an expansion of ectotherms like fish toward their poleward
boundaries. The novel data employed here demonstrates the added-value of scrutinizing
climate change perturbations on ecosystem thermal niches across the water column with
respect to surface data. We find that ongoing climate change will generate changes across the
water column in the upper and lower thermal range bounds on six OS stations. If anthropogenic
emissions continue to rise, we project that the lower bound of thermal ranges may cross the
upper limit of current thermal niches as early as ~2030 in subsurface waters (~50 – 1000 m),
potentially affecting their habitability. These changes can be delayed several decades with
immediate emission reduction consistent with a high mitigation scenario. In response to ocean warming, the shape of thermal niches will also change. We project that by 2100, depending on the vertical layer, thermal niches will be warmer and wider, potentially increasing the interspecific pressure; or warmer and narrower, forcing organisms to adapt to new local conditions or migrate. Assuming organisms are adapted to current environmental conditions, such changes may lead to rearrangements of marine habitats in the decades to come across latitude and, if possible, depth. These results shed light on a much more complex picture of the impacts of climate change to ecosystems by adding the vertical dimension.

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### Methods

**Ocean Sites observations**

The Ocean Sites (OS) network constitutes a worldwide effort to monitor ocean parameters through high-quality data extracted from long-term, high-frequency observations at several locations of the World ocean. Six OS stations, listed in Table S1, were selected because of the availability of continuous daily measurements of ocean temperature and salinity across the water column for more than seven years, allowing a robust computation of thermal range boundaries (see below). All of the six stations provide data from the surface to about 1000 m depth, that have been resampled daily at each depth, and then interpolated into the vertical grid of CNRM-ESM2-1.

Observational data is accessible through [http://tds0.ifremer.fr/thredds/catalog/CORIOLIS-OCEANITES-GDAC-OBS/DATA/](http://tds0.ifremer.fr/thredds/catalog/CORIOLIS-OCEANITES-GDAC-OBS/DATA/). Last accessed was in October 2020.

### Simulations

This work exploits simulations from a state-of-the-art Earth system model, CNRM-ESM2-1\(^2\), that has been developed by the CNRM-CERFACS climate group for the sixth phase of the Coupled Model Inter-comparison Project (CMIP6\(^3\)). The ocean component of CNRM-ESM2-1 is NEMOv3.6\(^4\), which resolves ocean dynamics on an eORCA1 grid\(^4\) with 75 vertical \(z\)-coordinate levels. This grid offers a horizontal resolution of about 1° with a grid refinement up to 0.3° in the tropics.
In this study, we performed four simulations with CNRM-ESM2-1: a 250 year-long pre-industrial control simulation (without anthropogenic forcing) to estimate the model’s internal variability; and a historical simulation from 1850 to 2014 followed by two future scenarios from 2015 to 2100, which are used to derive present and future variations in temperature minimum and maximum.

These simulations were produced using the external forcing as recommended by CMIP6 for the pre-industrial state and the historical period. For the future scenarios we used contrasting pathways: a low (SSP1-2.6) and high (SSP5-8.5) emission pathways as described in ref. 30.

All simulations provide daily outputs from the ocean surface to 4000 m for ocean temperature and salinity as well as oxygen, pH and net primary productivity. Here, we exploit only the first 47 vertical layers for ocean temperature and salinity in order to describe the first 1000 m depth of the water column. Finally, to ensure both observations and model data (historical + SSP5-8.5 simulation) cover exactly the same period, model data was selected to begin and end at the same date as observations.

**Ocean domains informed by Ocean Site stations**

Though OS networks are located throughout the World ocean, our selection of OS stations is disproportionately located in the North Atlantic and North Pacific oceans (see Fig. 1 and Table S1). To assess how large is the surface area of ocean domains informed by our six selected OS stations, we compute the level of similarity between daily profiles as provided by observations and the model hindcast over the current period (1990-2020) using the statistical approach presented in ref. 50. This approach compares simultaneously the mean and the daily variations of OS daily profiles with a neighbour grid-point model profile using a Chi-squared-based test. The test consists in comparing the cumulative sum of the Welch’s $t$ across depth levels to an empirical Chi-squared distribution with 47 degrees of freedom (i.e., the number of depth levels). We use 10,000 random samples of this Chi-squared distribution to estimate the empirical distribution of the Chi-squared law. The distribution is then used to compute an empirical ‘integrated’ p-value that represents an objective metric to determine how far the two profiles are consistent between each other within the depth interval.

The empirical ‘integrated’ p-value allows us to quantify the match between profiles. We establish a threshold of 0.90 to consider a profile over a grid-cell consistent with the OS profile. For
further analysis, stations were grouped into three ocean domains: polar, temperate and tropical waters.

Estimation of thermal niche boundaries

The working definition of the thermal niche employed in this work assumes that the species' tolerance ranges reflect the magnitude of the local temperature variability. As a consequence, we infer the vertical structure of the thermal niche from the lower and upper limits of the thermal range that is captured by the minimal and maximal environmental temperature across the water column.

Thanks to high-frequency data, we provide a robust yearly estimate of these bounds using the annual first (p01, Tmin) and last (p99, Tmax) percentiles of both model and observation temperature time-series at each depth level. In order to minimize the influence of the internal climate variability when comparing model and data results, we estimate model annual percentiles by grouping the three ensemble members. Thus, model percentile for thermal range is derived from a 365*3=1095 sample of daily outputs at each depth.

The breadth of thermal ranges are estimated as the difference between Tmax and Tmin at each depth level. Midpoint temperatures (Tmidpoint) correspond to the arithmetic mean of Tmin and Tmax, thus assuming normality in the distribution of Tmin and Tmax.

Tmin crosses thermal niche thresholds

To track future changes in the thermal range boundaries, we employed a method inspired from the well-established Time of Emergence (ToE) approach (see Supplementary Material). As for the ToE approach, our method requires estimates of a climate change signal (S). We estimate it using daily model outputs from 1850 to 2100 for an ensemble of three realizations from CNRM-ESM2-1 that has been run following historical and low emission SSP1-2.6 and high emission SSP5-8.5 pathways. For each pathway, we define S as the smooth spline (four degrees of freedom) of the variation of Tmin during the full simulation. In general, the ToE approach is defined as the first year at which S surpasses twice the standard deviation of the internal climate variability. Here, in contrast, we make use of different thresholds that have a meaning for ecosystem functioning, which represent key characteristics of the thermal range, Tmidpoint and Tmax. These two thresholds are defined as the average of a smooth spline (four degrees of
freedom) of the variation of Tmidpoint and Tmax during the past 30 years from today (1990 to 2020); a period considered to be representative of the current period.

For illustration purposes, we illustrate how our approach works for four depth levels of HOT-01 station (Fig. S5).

### End-of-the-century thermal niches

End-of-the-century thermal niches provide a snapshot of the concomitant changes in thermal range boundaries resulting from climate change. We compute the end-of-the-century thermal niche from daily data over the 2080-2100 period. Fig. 4 displays the end-of-the-century thermal range anomalies of both Tmin and Tmax with respect to the mean over 1990-2014, corresponding to the last years of the historical simulation. To compare with the historical profiles, we also include their anomalies. At each depth level, we assess the magnitude of the changes between the end-of-the-century and the historical profiles.

As changes in thermal range boundaries can evolve in both directions, and with a different pace, they may result in a re-arrangement of the vertical shape of the thermal range. To track if end-of-the-century thermal niches are also wider or narrower, we compute the difference between Tmax and Tmin anomalies at each depth level (Fig. S6). If the difference is positive, thermal niches will be wider, i.e., Tmax warms more rapidly. If the difference is negative, thermal niches will be narrower, i.e., Tmin warms more rapidly. If differences are < 0.05 ºC (i.e., level of uncertainty informed from the analysis of the internal variability of thermal range profiles in Fig. S4), we consider no changes in the shape of thermal niches will take place, i.e., only shifting toward warming or cooling is projected. Both emission pathways are displayed in Fig. S6.

In Fig. 4 we have assigned a colour code for each of these developments. A depiction of these developments is provided in Fig. S2.

### Model internal variability

As a consequence of the chaotic nature of processes in the Earth systems being simulated (ocean-atmosphere-land-biosphere-cryosphere), one of the main sources of uncertainties in climatic future projections is their internal variability. One way to isolate these uncertainties is
to generate an ensemble of model realizations\textsuperscript{53}. Here we make use of an ensemble of three members in order to minimise the influence of the internal variability in our computation. Each realization starts from different initial conditions of the model of Dec 31st 1980 (member 1), 1900 (member 2), and 2000 (member 3), sampling different states of the model climate.

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Data availability Interpolated data presented in the paper will be available through the Zenodo repository.

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