Department for Environment Food & Rural Affairs

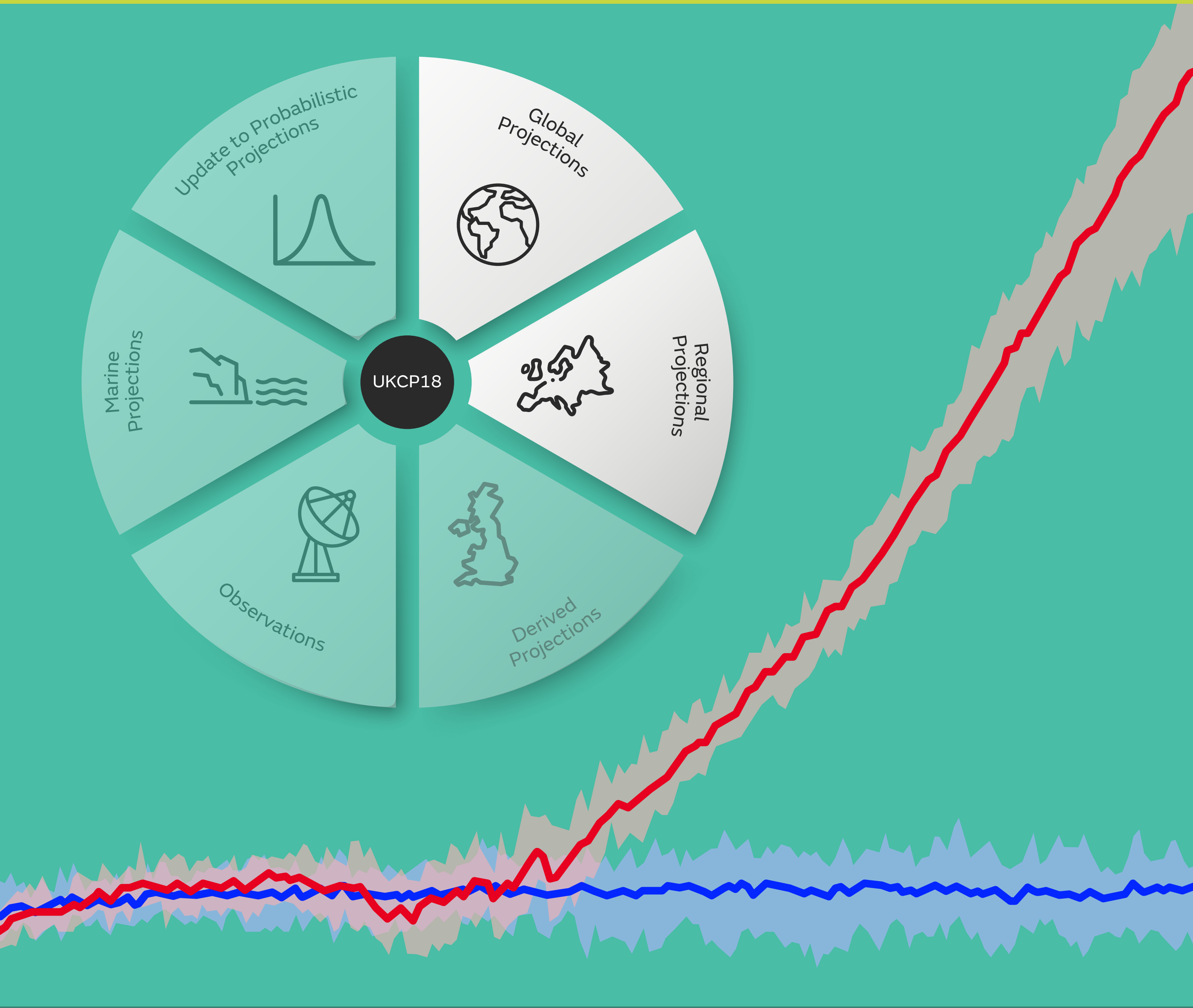
Department for Business, Energy & Industrial Strategy

Met Office Hadley Centre

Environment Agency

Assessment of drifts and internal variability in UKCP projections

September 2020



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Executive summary

Background: UKCP Global (60 km) consisted of 28 realisations of climate variables for 1900-2100 as simulated by 28 coupled ocean-atmosphere climate models. The 28 realisations consisted of 15 variants of the HadGEM3-GC3.05 global climate model (GCM) developed at the Met Office Hadley Centre (MOHC) and 13 other climate models from around the world. The UKCP18 Land Projections Report (Murphy et al. 2018) flagged that there was a potentially spurious change in global temperature in the first 40 years of the historical simulation for member 01. This report investigates this further for all 15 MOHC model variants, and provides some user guidance on the issue of model drifts (next page) followed by some technical detail (sections 1-4). Key points are:

- Spurious long-term changes, or "drifts", can occur in any GCM simulation, for reasons associated with the experimental set up. Control GCM simulations, in which anthropogenic and natural external forcings are held fixed at pre- or early- industrial values (we use 1900), are used to expose these drifts. A drift seen in a control simulation will also affect GCM simulations where the anthropogenic forcing is varied, such as the UKCP Global projections.
- In the 15 MOHC simulations, the largest drift occurs in temperature for the first 30 years of the simulations, providing a spurious increase of 0.2 °C in that period. This drift comes mainly from the Tropics and the Arctic. Most users only use data from a more recent period onwards, usually from 1961 or 1981, and this drift does not affect projected changes calculated this way. The user guidance provides advice if data prior to 1940 is being used.
- After 1940, 13 of the 15 control GCM simulations are essentially steady in global mean temperature with any drift being an order of magnitude smaller than the projected changes. We advise that there is no need to adjust UKCP projections for these small drifts. This also applies to temperature and precipitation in the UK from UKCP Global (60 km), UKCP Regional (12 km) and UKCP Local (2.2 km) projections, as well as most worldwide regions in UKCP Global. An exception is that a few amongst the 13 members show temperature drifts around Antarctica.
- The two exceptions are members 11 and 12 (for which there are 60 km, 12 km, and 2.2 km versions), which show steady weakening of the overturning circulation in the Atlantic Ocean. The user guidance states that if both members 11 and 12 stand out from the other 13 members for a climate variable of interest, then it is very likely related to the drift in the Atlantic Ocean and the two members should be excluded from the user's analysis. If, however, only one of these two members stands out then the Atlantic drift could still be playing a role, but a user would be justified in including both these members. However, both members are examples of an early collapse of the Atlantic overturning circulation, so could be used to develop a storyline to cover this type of event.
- The control simulations show that internal variability in the North Atlantic Oscillation and UK temperature and precipitation varies across the 15 MOHC variants.

User guidance

Our advice for dealing with the consequences of any drifts in the projections, based on the analysis in this report, is designed to be easy to apply, and to work without the need to involve data from the control simulations. There are two sections depending on whether you are looking at data for changes relative to a recent baseline period, or if you are interested in pre-1940 data.

Analysis of UKCP Global, Regional, and Local projections for changes relative to a recent baseline period

- For users of UKCP Global, Regional, or Local projections looking at data post-1940, there is no impact on any analysis that you have already carried out unless you have found members 11 and/or 12 (referred to as r001i1p02305 and r001i1p02335 on UKCP User Interface) behaving very differently to the rest of the ensemble.
- Members 11 and 12 experience a spurious, steady weakening of the strength in Atlantic overturning circulation. You need to check if they stand out from the other 13 MOHC variants (which also have ids starting with "r001i1p0") for the climate variable of interest. If both do, then it is likely that the Atlantic drift is causing this, and you should exclude those two members from your analysis. If, however, only one of these two members stands out then the Atlantic drift could still be playing a role, you would be justified in including both these members. However, members 11 and 12 are examples of an early collapse of the Atlantic overturning circulation, so you might be interested in using these two members as examples of this type of future storyline.
- Members 11 and 12 are two of the members used in the UKCP Regional (12 km) and UKCP Local (2.2 km) projections, that is, two of the projections that were downscaled to 12 km using the Regional Climate Model (RCM), and 2.2 km using the Convection Permitting Model (CPM). The same advice applies to the two RCM and CPM simulations driven by members 11 and 12.
- This advice applies anywhere in the world except near Antarctica (in particular, the Weddell Sea) where there are drifts. You should not analyse regions near Antarctica in the UKCP Global projections.

Analysis of Global Projections prior to 1940

- Prior to 1940 there is a drift in temperature, notably a rise of 0.2 °C in global temperature which occurs mainly in the Tropics and Arctic. You should consider whether the early drift might affect your analysis based on the technical part of this report. We advise testing whether omitting data prior to 1940 makes a significant difference to your results and your decision. If it does, do not use the data prior to 1940; otherwise it is fine to use the full data set.
- The previous point applies worldwide in UKCP Global. It does not affect the UKCP Regional or Local Projections, as they start after 1940.

As our advice does not require data from the control simulations, we do not plan to release the data that is analysed in this report. Research users wishing to further investigate the drift results or to analyse internal variability in the simulations should contact the UKCP helpdesk in the first instance to discuss options.

1. Introduction

The UKCP18 Global Projections consisted of 28 climate simulations. Members 16-28 were based on 13 different Global Climate Models (GCMs) from the CMIP5 archive. Members 01-15 were based on 15 variants of the latest Met Office Hadley Centre climate model, HadGEM3-GC3.05 (hereafter GC3.05-PPE). The 15 variants were generated by assigning different values to 47 model parameters, numbers in the GCM that control the strength of sub grid-scale processes that can affect historical and future climate. Only the HadGEM3 ensemble members are considered in this report. Each simulation provides a plausible[1] realisation of the historical and future climate. Ideally, these realisations should consist only of a response to anthropogenic forcing ("human-induced climate change") and a realisation of internal ("unforced") variability. In practice, technical issues with the experimental set up of any GCM simulation can introduce spurious long-term changes called "drifts" (Sen Gupta et al. 2013). These drifts are not due to climate change or multidecadal internal variability but can be mis-interpreted as either of these two factors in the absence of any further information. Control GCM experiments, in which the anthropogenic and natural forcing (e.g. solar and from volcanic eruptions) are held fixed over time, can be used to expose these drifts on time scales longer than multi-decadal internal variability.

Drifts can occur for a number of reasons (see below for four examples relevant to the UKCP18 Global Projections). Such drifts can manifest, in particular, in an imbalance between the global heat and water fluxes[2] exchanged between the ocean and atmosphere. In UKCP18, we had two preliminary phases of coupled simulation, before we ran the historic phase from 1900-2005 and the future phase from 2005-2100 (see UKCP18 Land Projections Report for more details). The first phase calibrated "flux adjustments" for member 01, the standard variant. The flux adjustments, which have a seasonal cycle, are added to the model at each time step and on average reduce, but do not necessarily eliminate, imbalances in the net surface heat and water fluxes. For the other members 02-15, we already had an estimate of the change that their parameter combinations made to the net global top-of-atmosphere (TOA) energy flux from separate atmosphere-only experiments. So, for each member, a globally uniform value was added to the heat flux adjustments calibrated for member 01 to offset differences in the net TOA flux. The water flux adjustments were not adjusted beyond member 01, so each member uses the values calibrated for the standard variant.

The flux adjustments are included in all subsequent phases of the coupled simulation. The second phase, which is called the "spin-up", involves continuing the adjustment of the ocean and its surface exchanges towards equilibration. For the purposes of the UKCP18 simulations, an approximate balancing of the surface fluxes to fixed pre- or early-industrial forcing was taken as a practical indication of an acceptable degree of equilibration (see section 2 for details). The later phases are where the anthropogenic forcing is applied. In UKCP18, the third phase was the historical simulations from 1900-2005.

[1] Plausible is a subjective term. Here it means that the coupled climate simulation and its atmosphere-only configuration passed acceptability criteria. For the atmosphere-only simulations of present day, this means they passed both an objective acceptability criterion based on several climate metrics, and a qualitative assessment of the climate in the North Atlantic/Europe sector. See UKCP18 Land Projections Report (Murphy et al. 2018) for details of the acceptability criteria.

[2] A flux is defined as the amount at which a quantity is transferred per unit area per unit time to or from a surface.

There are four issues with our experimental set-up which could potentially cause drifts. The first potential issue occurs if the spin-up phase is not long enough and equilibration is incomplete, particularly in the deep ocean. Our spin-ups were 80-100 years long, which is a short enough period for this issue to remain a possibility. The second issue arises because the flux adjustment method is imperfect, for members 02-15, due to the neglect of member-specific regional variations in the required heat flux adjustments, and of both regional and global variations in the required water flux adjustments. Both these issues would lead to a continuation of any drift in the spin-up phase. The third and fourth issues arise from two inconsistencies between the GCM configuration used in the spin-up phase and the one used in the later phases. Such changes potentially can cause sudden changes to the fluxes and therefore the simulation may adjust rapidly and then "drift" to find a new balance between the fluxes. The two changes were:

- After the spin-up simulations, an error was found in the soil hydraulics scheme. The movement of water through the soil is modelled using the van Genuchten equations (Van Genuchten 1980), whereas parameter values that determine the hydraulic conductivity for different soil types had been determined using a different set of equations (Brooks and Corey 1964). This leads to insufficient vertical transfer of soil moisture. This error was corrected for the later phases. Tests showed changes to local runoff but no appreciable changes to the freshwater budget at the scale of ocean basins.
- For the spin-up, present day land use changes were used. For the historical and future phases, land use became time-varying, using changes based on observations from 1900 to 2005, and values prescribed from the RCP8.5 scenario out to 2100. This leads to an artificial "jump" from the spin-up phase at 1900, with fewer grasslands and more shrubs and broadleaf and needleleaf forests.

For UKCP18, it was only possible to check for any drifts by running a single control simulation for the standard variant of the GC3.05-PPE (called member 01 here, and CTL-STD in the UKCP18 Land Projections Report). In section 3.3e of that report, Fig. 3.12 compared observed and simulated historical annual average temperature anomalies relative to 1901-1950. CTL-STD provided an additional illustration of internal variability, but also suggested a potential climate drift, which may explain a warming of ~0.2 °C during the first 20-30 years.

Control simulations have now been run for all 15 members of GC3.05-PPE. Whilst these simulations can be used to detect climate drift, they cannot easily attribute the cause of the drift to any single issue without extra information and detailed analysis. This report summarises the main results so that users of UKCP18 can understand the implications of any such drifts on any analyses. For instance, if there is an upward drift in the control simulation, then this implies that there is also an upward drift in the climate change simulation which can exaggerate the apparent response to anthropogenic forcing, potentially leading to over-adaptation. In contrast, a downward drift in the control simulation would lead to an underestimated level of climate change, potentially leading to under-adaptation. Note, that this description of the effects of drifts can become more complicated when climate change becomes nonlinear e.g. when sea ice has largely melted or a slowdown in the rate at which the overturning circulation in the Atlantic weakens (Good et al. 2015). These non-linear affects are most relevant to research users focusing on particular regions. They do not change the guidance contained in this report for most users in most situations.

Control simulations can also provide information on year-to-year variability, albeit for a fixed-forcing scenario rather than a scenario where emissions have been increased substantially. Year-to-year variability is an important part of the adaptation challenge as it represents the range of weather associated with human-induced climate change that we experience and have to cope with. Extreme weather is the most notable aspect of this year-to-year variability. Much of the 20th century year-to-year variability and extremes will be naturally occurring, that is, unforced and not due to man-made climate change. As the climate response increases, year-to-year variability will arise from interactions between this internal climate variability and the developing forced changes. The control runs allow us to assess the unforced, internal variability, how it varies across the members, and the extent it can contribute to extremes. A control simulation that shows no significant, long-term drift can be used to estimate the magnitude of internal variability under the fixed-forcing scenario, and to understand its physical characteristics. Such an estimate can then be compared against year-to-year variability about the trend in the climate projections, to detect any change in the magnitude of internal variability under climate change.

In section 2, the long-term drifts in temperature and precipitation around the world and for the UK are described. In section 3, we analyse the magnitude of selected aspects of internal climate variability in GC3.05-PPE, relevant to the UK region. In section 4, we summarise the results which then form the basis for our user guidance. We also discuss some of the implications that our analysis has for the future design of UKCP projections.

2 Long term drifts

The figures in this section show results from the control simulations, plotting time from years zero to 200. This is because the control simulations are not projections of 20th and 21st century climate, due to their use of fixed external forcing conditions. Nevertheless, year zero does correspond to 1900 in the initialisation of the historical climate change simulations, so time counted from year zero in each control run provides an indication of the likely development of any climate drift contribution, relative to 1900, in the corresponding UKCP18 simulation.

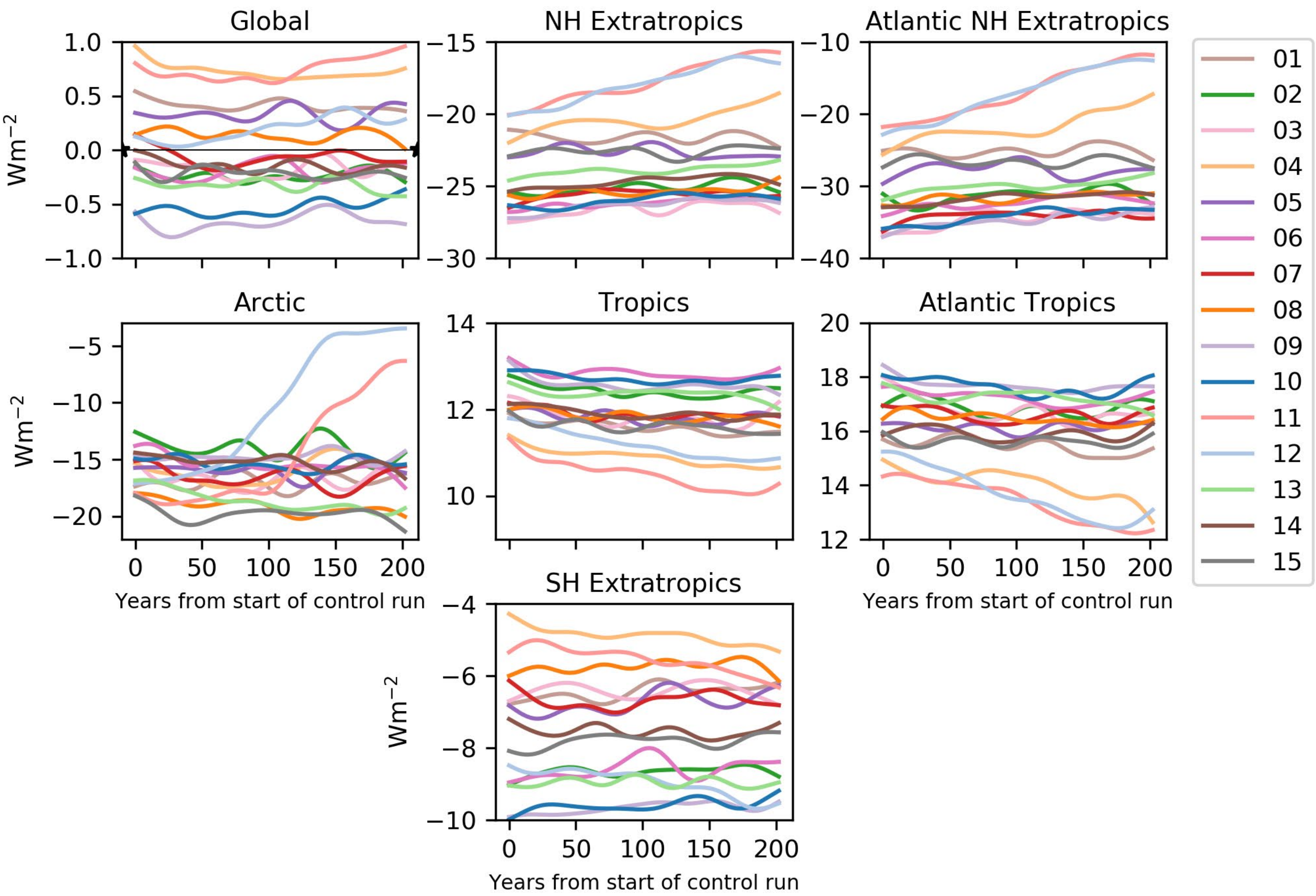

Figure 1. 50-year low-pass filtered[3] averages of the net surface heat flux into the ocean in 15 control simulations, for seven different regions of the globe. The diagnostic is the sum of the simulated flux and the flux adjustment contribution. Year 0 corresponds to 1900, the year that was used in the initialisation of the historical simulations (see text for more details). Colours indicate size of the global correction made to the flux adjustment (as explained in the text - reds and oranges indicate the members where most heat needs to be added to the ocean by the global correction, blues and purples indicate those in which most heat needs to be taken out of the ocean; intermediate values are represented by other colours. These colours are used in other figures that compare time series from different ensemble members). Member 01 is the standard variant.

[3] Before filtering, the trend over the first and last 20 years is extrapolated to extend the time series at each end by 20 years. Once the filter has been applied, these extended years are removed. This procedure is applied to all filtering used in this report.

The most important cause of drifts in global temperature is an imbalance in the net heat flux into the ocean. This is calculated as the sum of its dynamically simulated values, which vary with time, plus the prescribed, time-invariant contribution from the heat flux adjustment. The global mean ranges between -0.75 and 1 Wm-2 (see Fig.1 top left), though most are between +/-0.5 Wm-2. Having gone through a spin-up phase already, the time series remain steady over time. The total heat flux is also steady for the tropics, the Pacific (not shown) and the Southern Ocean but there are drifts in the North Atlantic, the Atlantic Tropics, and the Arctic, most notably in members 11 and 12 but also member 04.

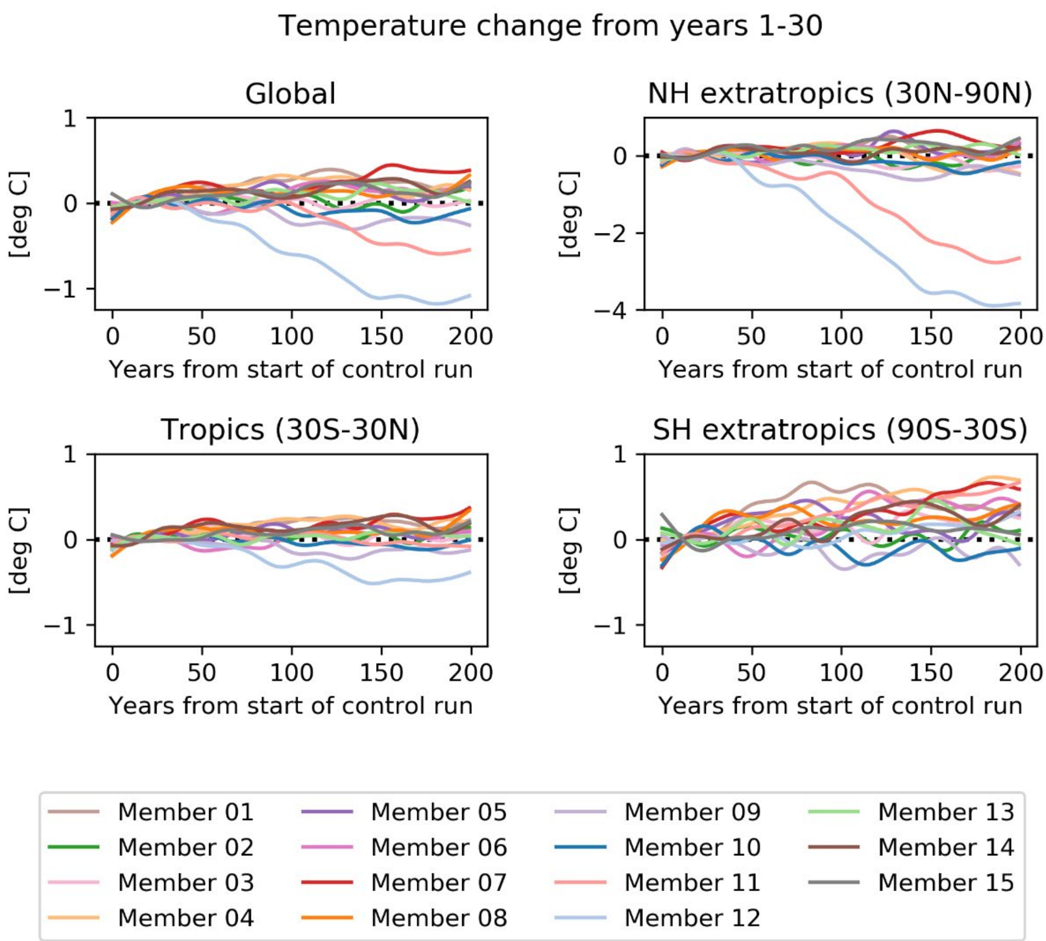

Figure 2. 30-year low-pass filtered time series of 1.5m temperature anomalies relative to the first 30 years for four different latitude bands.

To see the effect of these imbalances in net heat flux on variables relevant to climate impacts, we first look at temperature changes over various latitude bands (Fig. 2). The most obvious drifts are in the Northern Hemisphere (NH) extratropical temperature where members 11 and 12, which show a large upward drift in the net heat flux over the North Atlantic and Arctic (Fig. 1). In member 12, the evolving NH extratropical drift becomes large, lying between 1-2 °C during years 80-100 (equivalent to the UKCP18 baseline period of 1980-2000) and nearly reaching 4 °C by year 150, after which it reduces more slowly. In member 11, the drift is more modest (~ 0.5 °C) during years 80-100 but reaches about 3 °C by year 200, equivalent to 2100 in the climate change simulation. Despite looking similar to members 11 and 12 in terms of drifting Atlantic and Arctic surface fluxes, member 04 is not discernible from the remaining 12 members for temperature changes shown in Fig. 2.

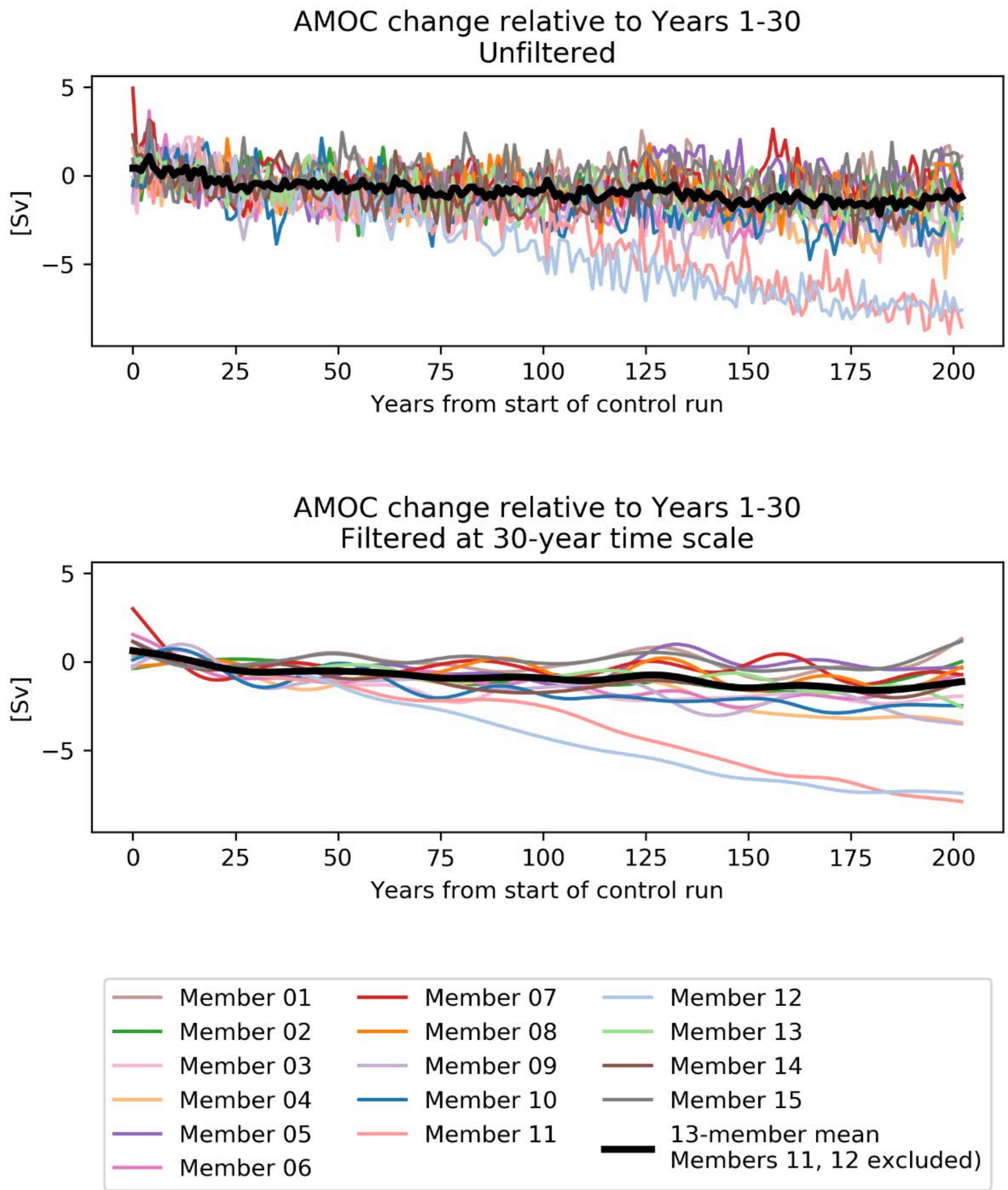

Figure 3. Unfiltered (top panel) and 30-year low-pass filtered (bottom panel) time series of AMOC anomalies relative to the first 30 years.

Drifts in these members 11 and 12 can also be seen in the Atlantic Meridional Overturning Circulation (AMOC) which is related to the northward transport of heat in the ocean (see Fig. 3). The AMOC is sensitive to heat and water fluxes at certain regions in the Atlantic and it is likely that the flux imbalance in those regions in these two members is driving the weakening of the AMOC and that this is driving the decrease in NH temperature. In comparison to the NH extratropics, the Tropics shows little drift across 14 members (member 12 drifts by 0.5 °C by year 150). The Southern Hemisphere (SH) extratropics shows a modest early temperature increase for Member 01 that then settles, whilst other members reach similar levels by the year 200. The ordering of the colours suggest that the long-term SH extratropical temperature rises are partly related to the global correction term indicated in Fig. 1. The AMOC also shows an initial drop of 1.5Sv in the first 30 years followed by a relatively steady period.

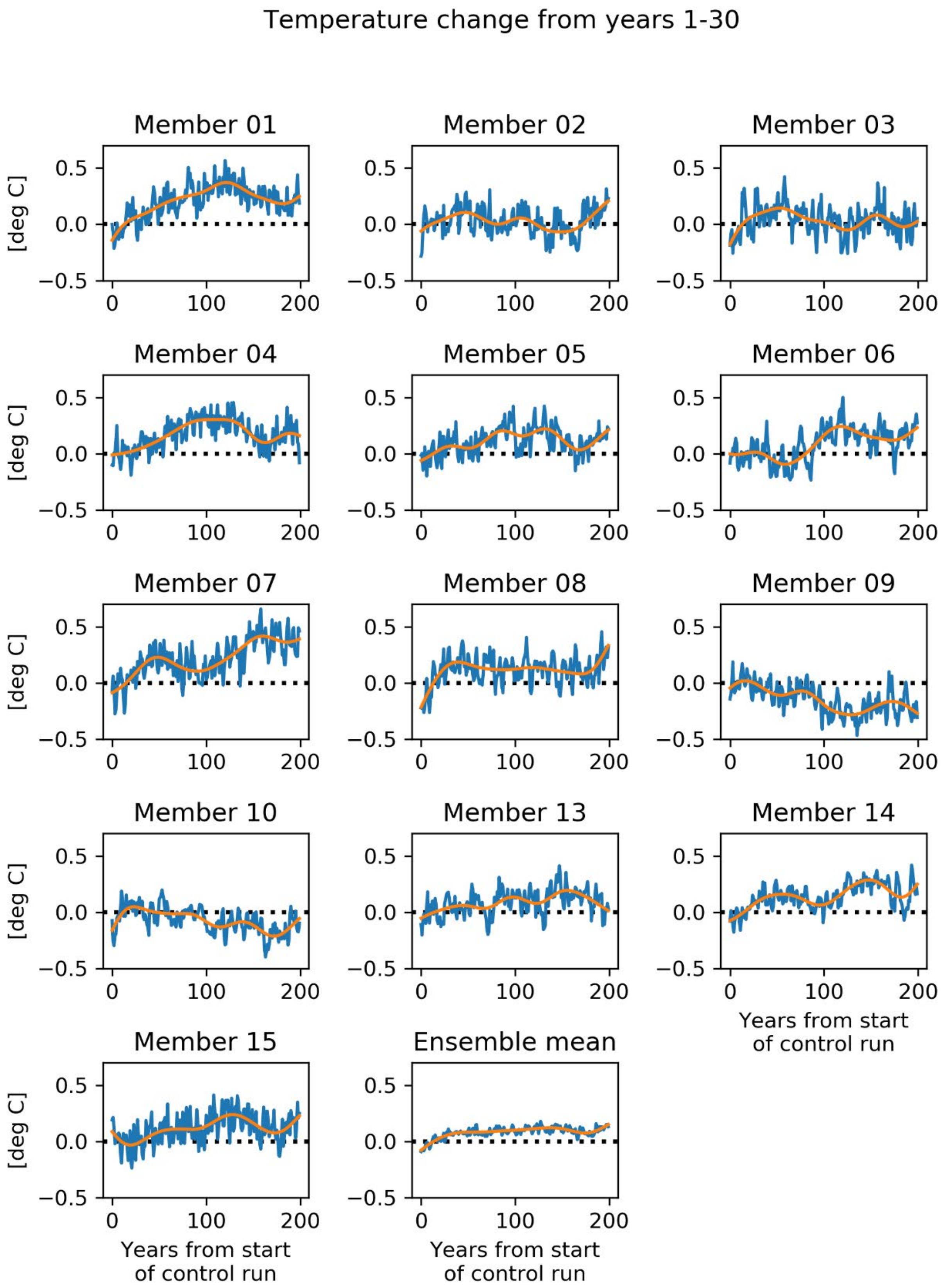

Figure 4. Global mean temperature anomalies relative to the average of the first 30 years for each member of GC3.05-PPE (excluding members 11 and 12) and the average of the 13 members (labelled "Ensemble mean"). The blue lines show unfiltered values. The orange values are filtered at 50-year time scales.

The only drifts that stand out for the global mean temperature are those of members 11 and 12. The different behaviour seen in these two members relative to the other members means that these two members will require different user guidance (see section 4). To explore drifts in global temperature more closely, Fig. 4 shows the global temperature drift for all members 01-15 except for members 11 and 12. This shows a range of behaviour across the different members where most members vary between -0.4 °C and 0.4 °C, some (members 01, 04) showing long slow variations whilst others (members 02, 08) remain steady. Only member 07 shows an upward drift of 0.5 °C over 200 years. Members 09 and 10 show the largest downward drifts but these are relatively small at about 0.2 °C over 200 years. Most members also show evidence of multi-decadal variability, illustrated most clearly by undulations in the low-pass filtered time series in members where the long-term drift is small. The other members are also likely to show multi-decadal variability; however, it is visually less clear in the presence of larger drift-related trends. An average across these 13 members (last panel of Fig. 4) has a temperature rise of 0.2 °C in the first 30 years followed by a steady period beyond that, where the other drifts and multi-decadal variability largely average out.

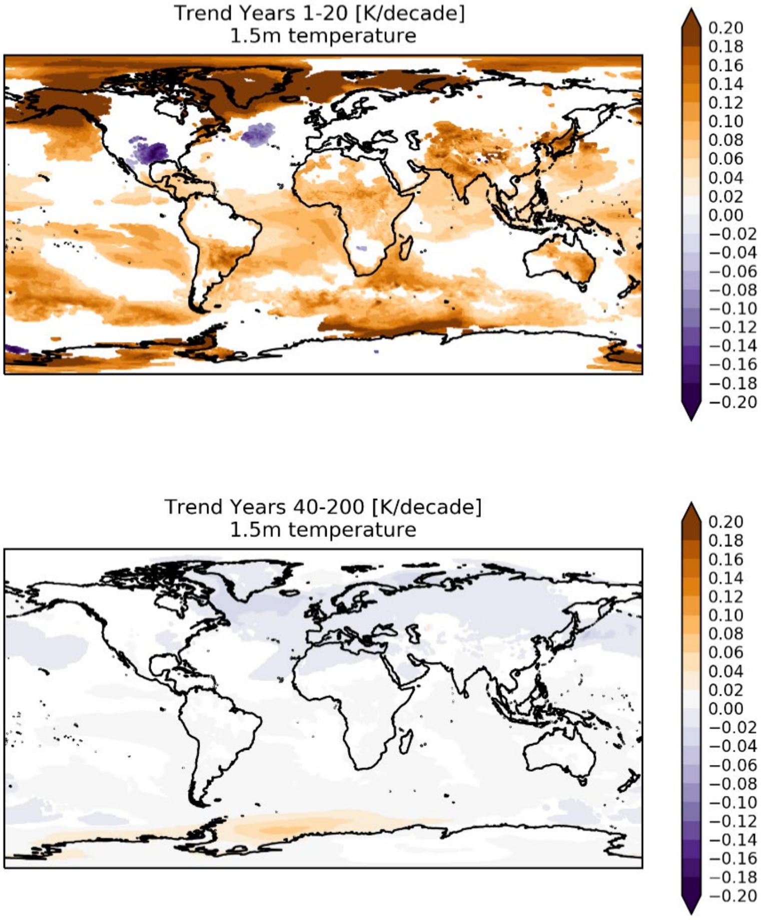

Figure 5. Map of the ensemble average 1.5m temperature trend at each grid point in K per decade for (top panel) years 1-20 and (bottom panel) years 40 onwards. Only grid points for which the trend is statistically significant at the 10% level[4] are shown.

[4] The trend test assumes white noise. A better statistical choice might be to fit red noise which means that less areas would be statistically significant. However, we opt for the simpler, over-confident white noise model as this plot is only used to indicate regions that might have drifted.

The cause of this relatively rapid adjustment of 0.2 °C in the first 30 years is likely due to changes in the fluxes relative to the preceding spin-up phase, caused by the third and fourth issues (related to the experimental set up) described in Section 1. The clearest difference between the last five years of the spin-up and the first five years of the historical phase is seen in the reflected shortwave radiation over regions where the land use changes were made (not shown). This suggests land use changes are driving the response. These changes initially warmed the land over much of the Tropics and south and central Asia (see Fig. 5 top panel). The stronger warming over much of the Arctic and the initial reduction in the AMOC over the first 20 years suggests these are more complicated responses to that initial warming. It is also possible that the change to the soil hydraulics played a role though we see no strong evidence for this. We do not explore these changes further.

From 40 years onwards (Fig. 5 bottom panel), the control runs (after excluding members 11 and 12) show that there is little drift over most regions. Near the UK, and over Atlantic and Eurasia, there is a downward drift of 0.2 °C per century but in the context of projected temperature changes of several degrees, this is small. For precipitation, there is hardly any drift (see Fig. 6).

The main drift in temperature after 40 years is near Antarctica, in and extending out from the Weddell Sea (see Fig. 5 bottom panel). This is the drift that is related to the upward global mean temperature drift seen in members 01, 06, and 07 (correlations of ~0.6 or more between Weddell Sea temperature rise and global temperature increase). More generally, Southern Hemisphere warming is related to less heat leaving the ocean (Fig. 1), and that leads to warmer SSTs and less sea ice. This can be seen by the ordering of the coloured lines in the bottom panel of Fig. 1, as the colouring is based on the globally uniform correction applied to each member's flux adjustments (red means heat needs to be added, blue means heat needs to be removed from the climate system at the top of the atmosphere). In the bottom right panel of Fig. 2, for the SH extratropical temperature, the order of the colouring is preserved reasonably well. This implies that the drift problem in the Southern Hemisphere is related to the global correction made to the flux adjustment. A similar ordering can be seen in the tropical temperature time series too. However, this cannot be the entire cause of the drifts in the Southern Ocean. For instance, the global correction does not apply to member 01, and in the first 80 years this control simulation drifts the most. In all GC3.05-PPE members, warm water moves south from east of South Africa and melts sea ice, thus exposing the underlying ocean and increasing the surface temperature. It is this that causes member 01 to warm there, and then as sea ice departs, the calibrated values for the flux adjustments are no longer necessarily optimal, hence further drift can occur. The global correction exacerbates the problem (most notably for member 04), and possibly offsets the problem for the other members (blue colours in Fig. 1).

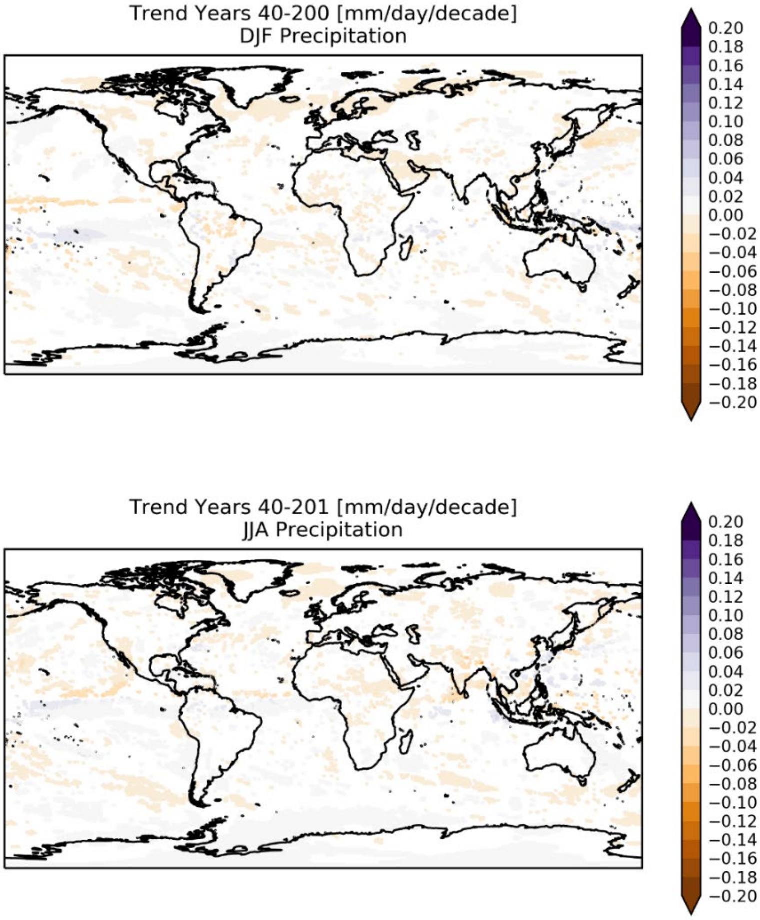

Figure 6. Map of winter (DJF) and summer (JJA) precipitation trend at each grid point in mm/day per decade for (top panel) years 1-20 and (bottom panel) years 40 onwards. Only grid points for which the trend is statistically significant at the 10% level are shown.

Fig. 7 shows that drifts in seasonal averages of UK temperature and precipitation changes are confined to members 11 and 12, which both have strong temperature drifts in all seasons but only in summer and spring for precipitation. This is in good agreement with Jackson et al. (2015) who describe similar responses to a slowdown in the AMOC driven artificially by a steady freshening of the North Atlantic.

Finally, we consider the main circulation driver of UK weather and variability in winter, the North Atlantic Oscillation (NAO). It is measured here as the difference in mean sea level pressure between Iceland and the Azores. Positive values indicate predominance of strong westerlies and the associated mild, wet winter weather. Fig. 8 (left panels) both show that there is no drift in the ensemble mean of the NAO.

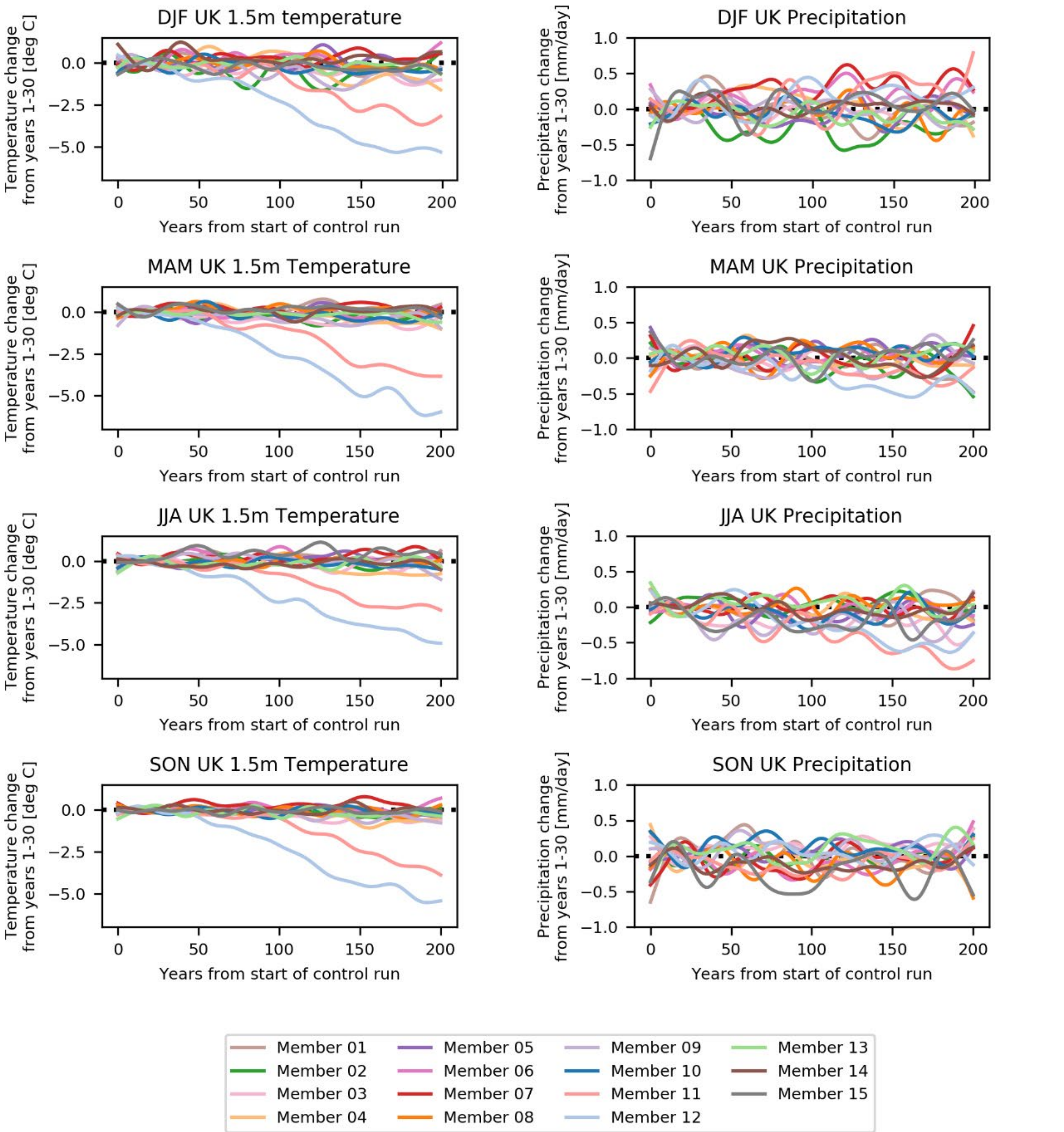

Figure 7. 30-year low-pass filtered time series of UK-average seasonal 1.5 m temperature and precipitation anomalies, relative to the first 30 years of the control simulations.

3. Year-to-year internal variability

Fig. 7 shows that for the UK, some of this year-to-year variability comes from multi-decadal fluctuations. We provide the analysis below so that users are aware that year-to-year variability is also a quantity that has a range of plausible values. Users may also be interested to understand which members have the most or least amount of internal variability. Fig. 8 top right panel shows that the amount of year-to-year variability varies between 7 and 9 hPa across the 15 members and there is no relationship to the climatological average strength of the NAO.

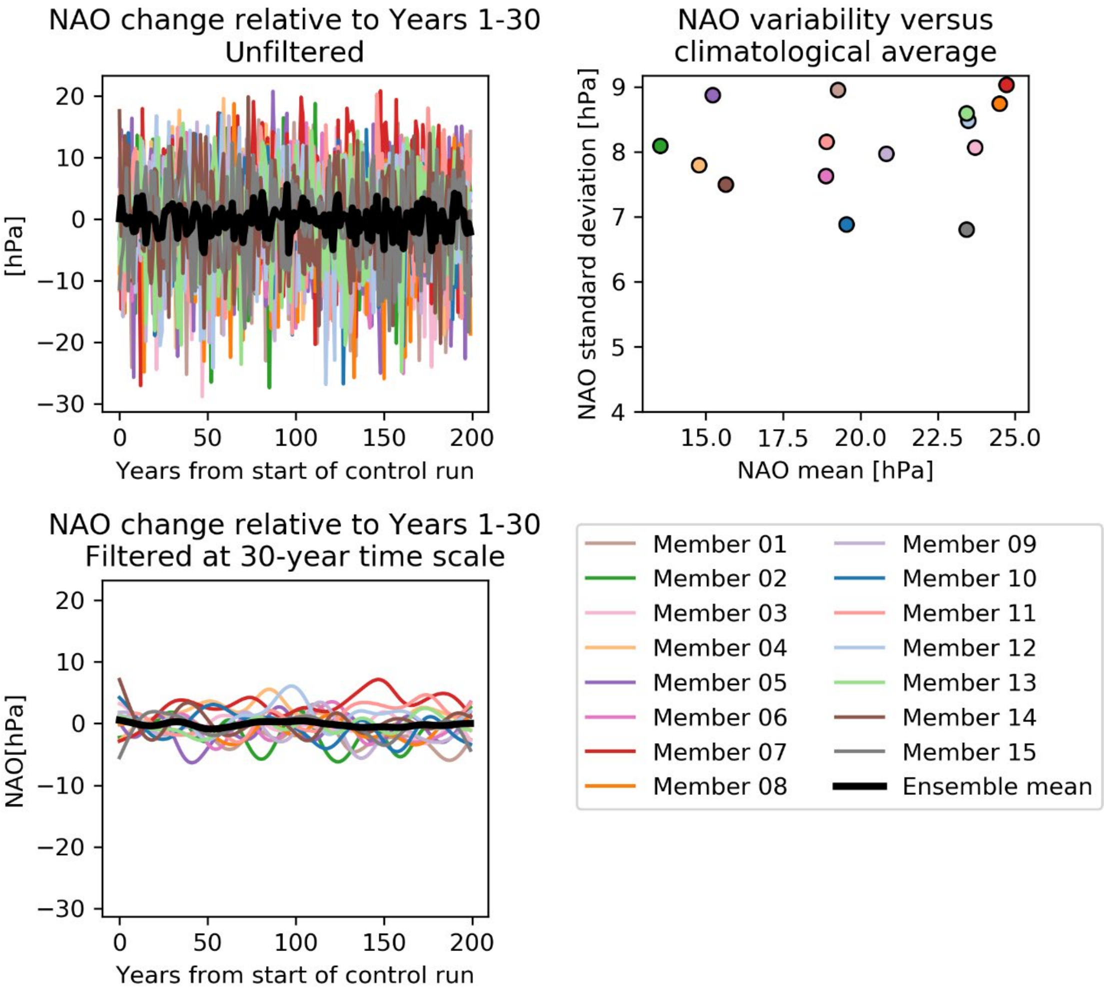

Figure 8. (top left) Unfiltered NAO anomalies from first 30 years; (top right) Scatterplot of NAO standard deviations of unfiltered NAO time series against the mean NAO across the 15 members; (bottom left) 30-year low-pass filtered NAO anomalies from first 30 years.

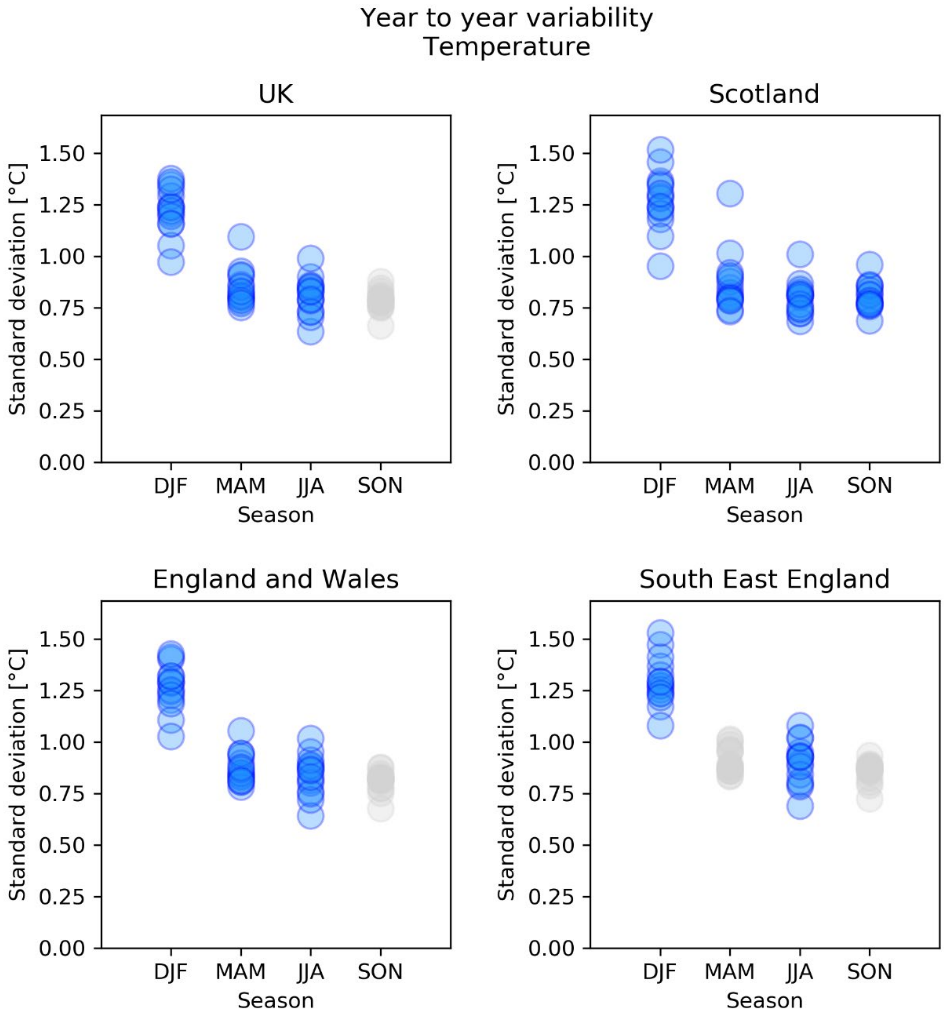

Figure 9. Standard deviation for each member 01-15 of seasonal mean temperature for 4 regions. Standard deviations are estimated from time series high-pass filtered to remove variability on 50-year time scales or longer. Blue dots indicate that the variances are statistically significantly different at the 5% level using Bartlett's (one-sided) test that each time series are sampled with equal variance.

Next, we consider internal variability of temperature and precipitation averaged over the whole UK and three sub-regions to represent differences across the UK. Internal variability (as measured by the interannual standard deviation in Fig. 9) in temperature differs across the members in a statistically significant way for winter, spring (except for South East England), and summer but not for autumn for three of the regions. The exception is Scotland, which has detectable differences in internal variability across all four seasons. Winter shows more variability than the other three seasons which have similar levels of variability. The range of standard deviation across members is about 50-60% in the seasons and regions where there is a detectable difference in variability.

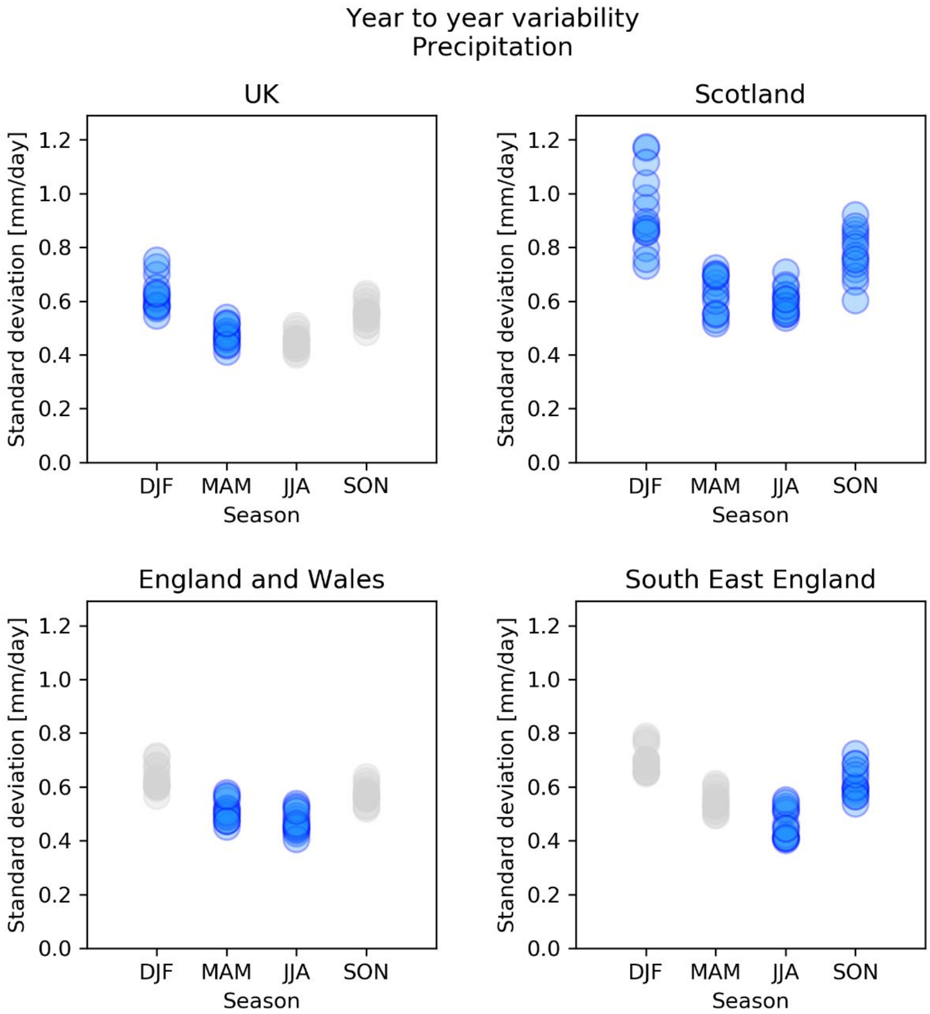

Figure 10. Standard deviation for each member 01-15 of seasonal mean precipitation for 4 regions. Standard deviations are estimated from time series high-pass filtered to remove variability on 50-year time scales or longer. Blue dots indicate that the variances are statistically significantly different at the 5% level using Bartlett's (one-sided) test that each time series are sampled with equal variance.

For precipitation (Fig. 10), there is a detectable difference in internal variability across the 15 members for all seasons in Scotland. For winter there, the greatest standard deviation is nearly double the lowest value. The next most variable season is generally autumn, though there is only a discernible difference between the 15 members for Scotland and South East England. The spread in summer variability is statistically significant in all three sub-regions but not the UK average itself. The spread in variability across members may be related to the average precipitation across members. Correlations between the average and standard deviation of precipitation across the 15 members, show three cases where the correlation value is high enough to explain at least half the variance: Scotland, UK, and South East England in winter (0.89, 0.81, and 0.71), and South East England in summer (0.84). England and Wales in winter (0.7) and summer (0.67), Scotland in spring (0.67), and South East England in Autumn (0.69) also have high correlations.

4. Summary and discussion

In summary, the control simulations exhibit both multi-decadal internal variability, which varies across the 15 members, and long-term drifts. The long-term drifts consist of:

- An initial adjustment to temperature and AMOC in the first 30 years mainly due to an artificial change in the land use and soil hydraulics scheme at 1900. This is common to all members 01-15 and has balanced out beyond 40 years.
- Some members, most notably 11 and 12, have drifts towards weaker AMOCs that persist for much of the simulation.
- There is a drift in the Southern Ocean, particularly near the Weddell Sea. It probably happens in all members. It is exacerbated by the global correction to the flux adjustments in some members. Member 01 has some extra drift, possibly due to nonlinear responses associated with sea ice melt. This may also be occurring in other members.
- Beyond 40 years, there is no appreciable drift near the UK, except for that associated with the AMOC weakening in members 11 and 12.
- More broadly, any drifts that do exist for other regions of the world (except for Weddell Sea and possibly the Arctic) are small relative to the size of the projected changes.

Our advice in the User Guidance section is based on this summary of the long-term drifts. Our main concerns are members 11 and 12, and drifts in the first 40 years. The first would affect the entire coupled simulation from 1900-2100 whilst the second would affect the historic phase only up to 1940.

One might consider adjusting UKCP Global using the drifts outlined in this report. However, our assessment is that bias correction[5] is not simple to implement, and there is no single, accepted standard approach. So, our user guidance is designed to be applicable without the need for the control data itself. However, research users wishing to further investigate the drift results or analyse internal variability in the simulations should contact the UKCP helpdesk in the first instance to discuss options.

[5] If bias correction was to be done for a single quantity, it would be important not to simply remove the control time series from the historical and future time series. This is because interannual and multi-decadal natural variability is not in phase across the two sets of simulations, and must be removed first from the control time series to expose the long-term drift. Furthermore, our investigation of the Weddell Sea analysis shows that the long-term drifts vary across the 15 members, and even with a much larger set of detailed diagnostics, it is still hard to isolate the drift from natural variability. For multivariate approaches, there is the added complexity of the need to maintain consistency between multiple variables.

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