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Impact of internal variability on projections of Sahel precipitation change

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Abstract

The impact of the increase of greenhouse gases on Sahelian precipitation is very uncertain in both its spatial pattern and magnitude. In particular, the relative importance of internal variability versus external forcings depends on the time horizon considered in the climate projection. In this study we address the respective roles of the internal climate variability versus external forcings on Sahelian precipitation by using the data from the CESM Large Ensemble Project, which consists of a 40 member ensemble performed with the CESM1-CAM5 coupled model for the period 1920–2100. We show that CESM1-CAM5 is able to simulate the mean and interannual variability of Sahel precipitation, and is representative of a CMIP5 ensemble of simulations (i.e. it simulates the same pattern of precipitation change along with equivalent magnitude and seasonal cycle changes as the CMIP5 ensemble mean). However, CESM1-CAM5 underestimates the long-term decadal variability in Sahel precipitation. For short-term (2010–2049) and mid-term (2030–2069) projections the simulated internal variability component is able to obscure the projected impact of the external forcing. For long-term (2060–2099) projections external forcing induced change becomes stronger than simulated internal variability. Precipitation changes are found to be more robust over the central Sahel than over the western Sahel, where climate change effects struggle to emerge. Ten (thirty) members are needed to separate the 10 year averaged forced response from climate internal variability response in the western Sahel for a long-term (short-term) horizon. Over the central Sahel two members (ten members) are needed for a long-term (short-term) horizon.

1. Introduction

Sahelian economies are closely associated with rain-fed agriculture and are thus highly vulnerable to precipitation change. Quantifying and understanding the future evolution of Sahel precipitation is therefore of primary interest for decision makers, especially for the near-term horizon (10–30 years), referred to as the 'decadal' time scale (Meehl *et al* 2009). However, climate projections of Sahel precipitation are still very uncertain, as highlighted by the analysis of Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations (Taylor *et al* 2012), summarized in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC; Barros *et al* 2015).

Uncertainties in simulating the regional effects of climate change are due to several causes: (a) model formulation and physics, (b) representation of the external forcings (volcanoes, greenhouse gases (GHGs), aerosols, solar radiation) and (c) the internal or intrinsic climate variability (IV hereafter). IV, which is also referred to as climate noise in the literature (Feldstein 2000 and Deser *et al* 2012), is due to non-linear dynamical processes generated by either only one component of the climate system or by coupled interactions among the atmosphere, ocean, land and cryosphere. Over the Sahel, low-frequency modulation of precipitation is associated with sea surface temperature (SST) variability, such as the Atlantic Multidecadal Variability (AMV, Knight *et al* 2006, Zhang and Delworth 2006, Ting *et al* 2009, Mohino *et al* 2011, Martin *et al* 2014 and Martin and Thorncroft 2014) and the Interdecadal Pacific Oscillation (IPO, see Villamayor and Mohino 2015) on mutidecadal time scales, the tropical Atlantic (Janicot 1992) and the El Niño Southern Oscillation (Joly and Voldoire 2009) on interannual time scales. Precipitation changes associated with these variabilities are able to exacerbate or offset the impact of the external forcing.

At the global scale, precipitation uncertainties in long-term projections are mostly due to differences between climate models (Hawkins and Sutton 2011). IV is often considered as constant while uncertainties due to the scenario and model increase with time. Thus, the relative uncertainty due to climate IV is strong for short-term projections (under 30 years) and decreases with time. In contrast, scenario uncertainty increases with time to become, at the global scale, the second largest source of uncertainty after one century (Hawkins and Sutton 2011).

At regional scales, over the Sahel, the scenario uncertainty has been shown to be relatively small (Hawkins and Sutton 2011). Fontaine *et al* (2011), Monerie *et al* (2012), Biasutti (2013), James and Washington (2013), Roehrig *et al* (2013), Skinner and Diffenbaugh 2014 and James *et al* (2015) support this statement: these authors have shown a similar spatial pattern in projected Sahel precipitation (e.g. an increase in precipitation over the central Sahel, a decrease in precipitation over the western Sahel), with different relative concentration pathways scenarios (RCPs). Although all scenarios lead to similar patterns of precipitation changes in the same model, the magnitude of the response is strongly modulated by anthropogenic GHG emissions (RCP4.5 and RCP8.5). Furthermore, although scenario uncertainty is relative small the model uncertainty is large, as highlighted from CMIP3 (Druyan 2011) and CMIP5 simulations (Monerie *et al* 2016b). Monerie *et al* (2016b) have shown that the CMIP5 multi-model ensemble exhibits a large spread in projected precipitation changes at the end of 21st century (ranging from a significant decrease to a significant increase), and the associated precipitation response is also found to be model-dependent. In the aforementioned study only one member for each climate model has been analysed and the impact of climate IV on the precipitation response has not been investigated.

The IV component of the Sahel precipitation is shown to be one of the strongest worldwide, contributing to a large amount of the Sahel precipitation changes (Hawkins and Sutton 2011). Yet, CMIP5 based studies often only include a few ensemble members (e.g. one to three members of each climate model), while more simulations are needed to properly assess the role of IV on the climate change effects (Deser *et al* 2012 2014, Hawkins and Sutton 2009, Hawkins and Sutton 2011). This issue leads to the statement that, globally, IV accounts for at least 50% of the inter-model spread in projected climate trends during the 2005–2060 period (Deser *et al* 2012). To date, in spite of its major importance regionally, no focus has been made on the role of IV in projects of the West African Monsoon (WAM). This study aims to fill this gap.

The main scientific questions to address can thus be summarized as follows:

- To what extent, and over what time-horizon, is IV able to offset the impact of increased external forcing for projections of precipitation change over the Sahel?
- How many ensemble members do we need to accurately estimate the forced response in precipitation over the Sahel?

This study is organized as follows. Section 2 presents the methods and simulations used. Section 3 quantifies the model errors, and section 4 separates the model-simulated internal variability vs. forced change. Section 5 quantifies the minimum number of simulations needed to properly estimate the forced response. The main results are next summarized and discussed in section 6.

2. Methods and data

2.1. Data

We use the 40 members of the Community Earth System Model (CESM) Large Ensemble Project (LENS, Kay *et al* 2015), hereafter noted CESM1-CAM5, a publically available set of climate model simulations intended for advancing understanding of internal climate variability and climate change. Simulations have been performed with the CESM version 1 (CESM1). CESM1 includes coupled ocean, land, atmosphere and sea-ice components. The Community Atmosphere Model (CAM5.2; Hurrell *et al* 2013) is the atmospheric model, CLM4 is the land surface component, POP2 the ocean model and CICE4 the sea-ice component. The same radiative forcing scenario (historical evolution in GHG concentration, volcanic forcing and anthropogenic aerosols) for the period 1920–2005 has been applied to all 40 members. This constitutes the historical (HIST) ensemble. From 2006–2100, the same RCP8.5 forcing has also been applied. The RCP8.5 is the most pessimistic scenario, prescribing a radiative forcing which reaches 8.5 W m^{-2} in 2100; see Meinshausen *et al* 2011). The members are obtained through perturbations of the initial atmospheric conditions. Details of the simulations are found in Kay *et al* (2015). The data are freely available on the National Center for Atmospheric Research (NCAR) website (www.cesm.ucar.edu/projects/community-projects/LENS/data-sets.html).

For observations, we used precipitation from the Global Precipitation Climatology Center (GPCC;

Becker *et al* 2013) dataset on a 1° × 1° grid resolution (version 7), available from 1901–2013, the precipitation from the GPCP v2.2 data set (Adler *et al* 2003), available for the 1979–2010 period with a 2.5° × 2.5° horizontal grid resolution, and the University of Delaware v4.01 precipitation data set (UDEL; Willmott *et al* 2001), available from 1901–2014 with a 0.5° × 0.5° horizontal resolution.

2.2. Method

In this study, the climate change effects on Sahelian precipitation are assessed by comparing a 'current period' (1960–1999 under the historical simulations) with a future period (under the RCP8.5 emission scenario), for both a 'short-term' (2010–2049) and a 'long-term' time-horizon (2060–2099). These periods are used to document the relative importance of climate IV on the projected precipitation change for both the first and second halves of the 21st century.

We follow the method described in Deser *et al* (2014) to separate the precipitation change into its internal and forced components:

- The precipitation change (Δpr) is the change obtained for a given member.
- The forced response ($\overline{\Delta pr}$) is the average of the precipitation change obtained from the 40 members (the forced response is thus defined by the ensemble mean).
- IV is obtained by subtracting the forced response from the precipitation change for each member individually.

We used the signal-to-noise ratio (SNR hereafter) to assess the relative contribution of the internal variability and the forced response, as

$$\mathrm{SNR} = \frac{\overline{\Delta pr}}{\sigma \Delta pr}$$

where $\overline{\Delta pr}$ is the forced response and the noise is defined as $\sigma \Delta pr$, the inter-member standard deviation of the projected change in precipitation for a given period. A SNR greater than 1 (less than 1) implies that the impact of the external forcing is stronger (weaker) than the climate IV, i.e. the impact of the external forcing does (does not) emerge.

3. Model evaluation

3.1. Interannual and interdecadal to multi-decadal variability

Since we assess the impact of IV on the forced response it is necessary to ensure that CESM1-CAM5 is able to simulate a reliable Sahel precipitation variability. We assume that a model which simulates too large (small) a precipitation variability will lead to an overestimation (underestimation) of the impact of the IV on the forced response. The following analysis may not then properly document the impact of IV on prediction uncertainties. We thereby evaluate the precipitation variability of observations and simulated by CESM1-CAM5 by computing the variance of the precipitation.

The observed precipitation variance (1979–1999) is the strongest over the coast of Guinea, with the maximum located over the Guinean mountains (figures 1(*b*)–(*d*)). Precipitation variability, along with the mean precipitation intensity, decreases northward from the Guinean coast to the Sahel, highlighting a zonal transition from the wet Guinean coast towards the dry Sahara desert (figures 1(*b*)–(*d*)). Precipitation variability is weaker in GPCP than in both GPCC and UDEL in the vicinity of Fouta Djalon along the Guinean coast and over the mountains of Cameroon because of a coarser horizontal resolution in the former. For CESM1-CAM5 we estimate the precipitation variance by computing the average of the interannual variance of each of the 40 members over the same time period (1979–1999) (figure 1(*a*)). The location and magnitude of the precipitation variance is well represented in CESM1-CAM5, in comparison with the observations. We therefore conclude that CESM1-CAM5 is able to simulate a consistent variability in precipitation over West Africa, with however a strong inter-member variability (figure S1, available at stacks.iop.org/ERL/12/114003/mmedia). We assume here that precipitation variance is representative of the natural precipitation variability (or IV). As a confirmation we computed the standard deviation of interannual Sahel precipitation (0.5–0.6 mm day^{-1} over the 1979–1999 time period), which is equivalent to the IV standard deviation obtained through decomposition between the forced and internal component (i.e. computed as the inter-member standard deviation: figures 6(*a*) and (*b*)). We therefore conclude that CESM1-CAM5 is able to simulate the IV over West Africa.

We cannot directly assess the ability of CESM1-CAM5 to simulate the future IV evolution, we thus hypothesise that IV remains constant with time, although slightly increasing during the 21st century (Boer 2009, also seen in figure 5). We therefore assume the comparison with observations over a current period (1979–1999) as robust for both historical and future evolution of the IV component.

We also assess the ability of CESM1-CAM5 to simulate the observed decadal variability in Sahel precipitation (figure 2(*a*) and figure S2). The CESM1-CAM5 ensemble mean (figure 2(*a*)), like most of the CMIP5 models (figure S2), does not reproduce the past multi-decadal evolution of the decadal Sahel precipitation. The power spectrum of the unfiltered Sahel precipitation (figure 2(*b*)) for CESM1-CAM5 and for GPCC and UDEL over the period 1920–2005 shows that CESM1-CAM5 is able to reliably produce the variability for timescales shorter than 15 years. In contrast, the multi-decadal variability in Sahel precipitation is underestimated in CESM1-CAM5.

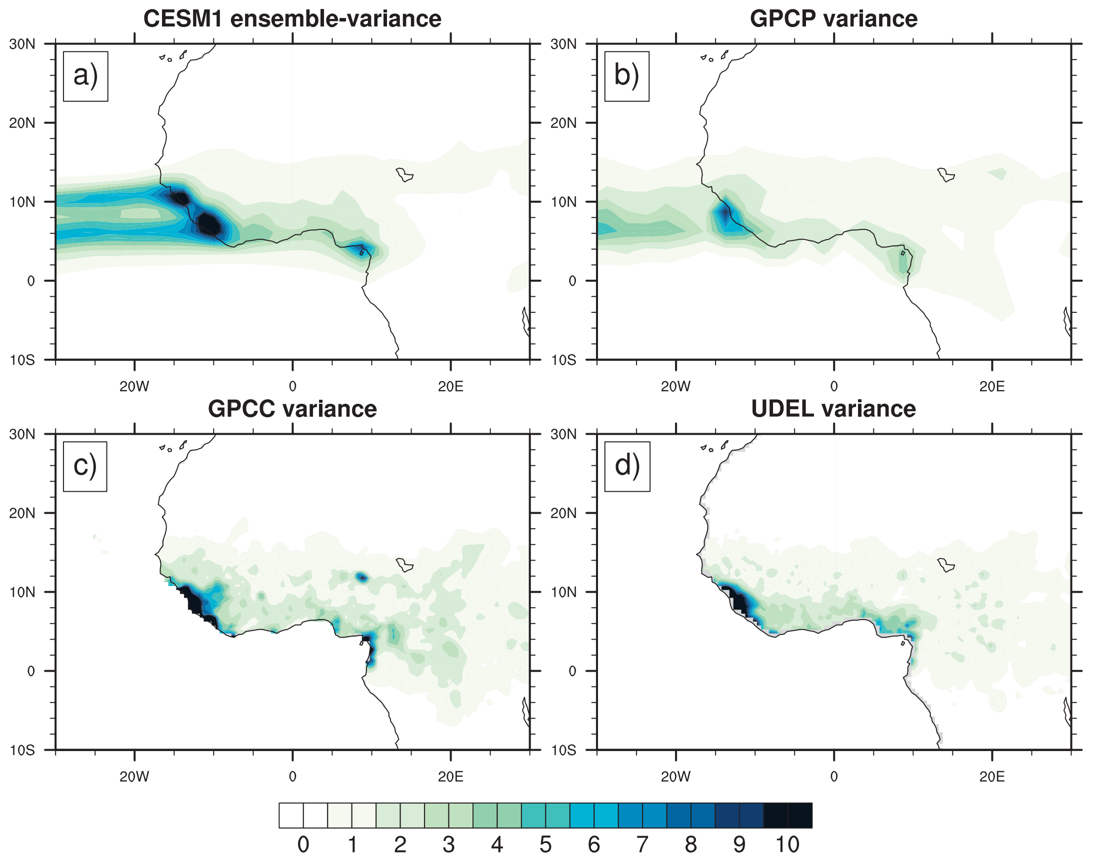

Figure 1. Precipitation variance (mm^2 day^{-2}) for (*a*) CESM1-CAM5, (*b*) GPCP, (*c*) GPCC and (*d*) UDEL. The variance is computed from the inter-seasonal (JAS) evolution over the 1979–1999 period. For CESM1-CAM5 we estimate the precipitation variance by computing the average of the inter-seasonal variance of each of the 40 members.

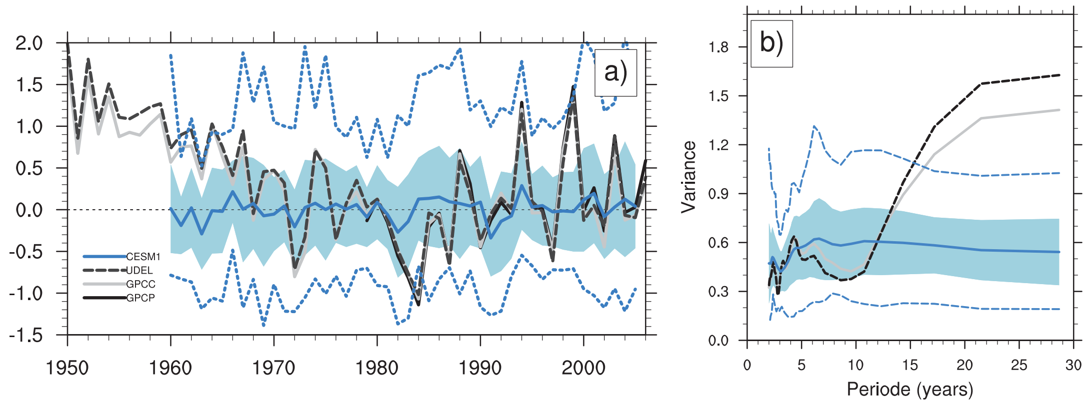

Figure 2. (*a*) Sahel precipitation change (mm day^{-1}; 10°N–20°N; 10°W–10°E) relative to the period 1979–1999 for CESM1 (blue line), UDEL (black dashed line), GPCC (grey solid line) and GPCP (solid black line). (*b*) Power spectrum of unfiltered and detrended summer Sahel precipitation (JAS; 1920–2005) for CESM1 (blue line), UDEL (black dashed line) and GPCC (grey solid line). In both panels the blue shading indicate the CESM1 precipitation spread, as computed from one inter-member standard deviation, and the blue dotted lines indicate the minimum and maximum values, as obtained from the ensemble member.

However, CESM1-CAM5 is not an outlier, as the underestimation of the multi-decadal variability of Sahel precipitation is a common feature among the CMIP5 archive (see Biasutti 2013, figures S2 and S3).

3.2. Future changes in Sahel precipitation

We first analyse the impact of climate change on the Sahel during the peak of the rainy season, that is, the July–August–September (JAS) period. Figure 3 shows a comparison between the projected mean precipitation and spread simulated by both an ensemble of CMIP5 models (33 models) under RCP8.5 conditions (figure 3(*a*)) and the 40 members of CESM1 (figure 3(*b*)). The CMIP5 ensemble exhibits a robust decrease (increase) in precipitation over the western (central) Sahel at the end of the 21st century during the monsoonal season (figure 3(*a*)). Here, only the precipitation increase over the central Sahel is found to

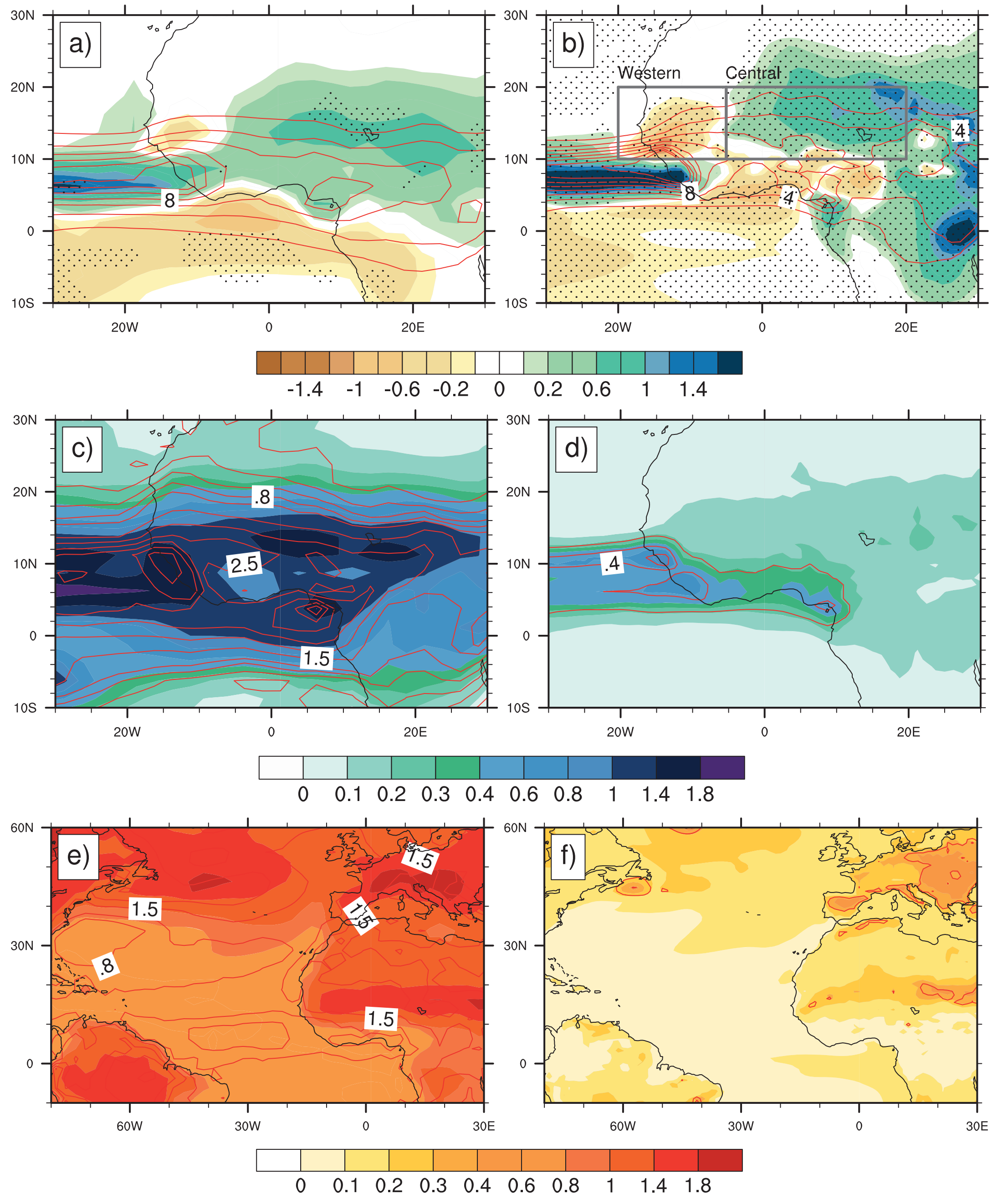

Figure 3. Precipitation change (mm day^{-1}) as obtained by the difference between the 2060–2099 (RCP8.5 emission scenario) and the 1960–1999 (historical emission scenario) for (*a*) a CMIP5 multi-model mean (33 CMIP5 simulations) and (*b*) the CESM1-CAM5 ensemble. Stippling represents the grid-points where at least 80% of the models/members agree with the sign of the intra-group ensemble mean within each groups. Spread (standard deviation) in projected precipitation change with (*c*) the CMIP5 and the (*d*) CESM1-CAM5 ensemble member (shaded in colour). Red lines represent the spread in simulating historical (1960–1999) precipitation. Spread in projected surface temperature change with (*e*) the CMIP5 and the (*f*) CESM1-CAM5 ensemble member (shaded in colour). Red lines represent the spread in simulating historical (1960–1999) surface temperature.

be robust (as simulated by at least 80% of the climate models). The projected changes over the western Sahel are uncertain in JAS. Projected changes are however stronger and more robust during the early rainy season, in June–July–August (JJA) (Biasutti 2013, Monerie *et al* 2016b). We found the same pattern of forced change for short-term projections (figures S4(*a*) and (*b*)), highlighting that the intensity of the external radiative forcing does not affect the precipitation change pattern.

CESM1-CAM5 exhibits the same pattern of precipitation change as the CMIP5 mean, together with comparable intensities (figure 3(*b*)). Moreover, both CESM1-CAM5 and CMIP5 ensembles project a northward shift of the monsoon cell, as shown by the decrease in precipitation over the tropical Atlantic and the increase in precipitation over the central Sahel (figures 3(*a*) and (*b*)). Therefore, in view of this similarity, CESM1-CAM5 can be considered as representative of the CMIP5 exercise.

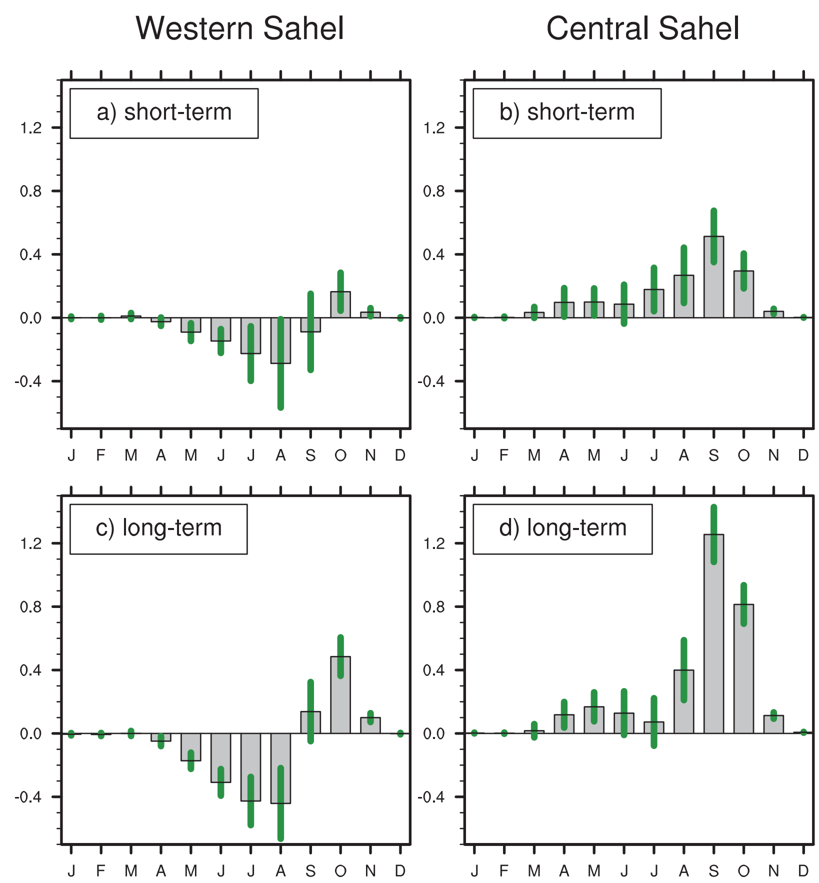

Figure 4. Precipitation change (grey bars; mm day^{-1}) over the western and central Sahel for short-term ((*a*) and (*b*); 2010–2049) and long-term ((*c*) and (*d*); 2060–2099) projections. The uncertainty, defined as the inter-member standard deviation, is represented by the vertical green line.

Note that precipitation change appears more robust for the CESM1-CAM5 ensemble than for the CMIP5 ensemble (see the dots on figures 3(*a*) and (*b*)). The spread in the CMIP5 multi-model precipitation change is strong over the Sahel and the maritime Intertropical Convergence Zone (figure 3(*c*)). It is even larger than the forced response, leading to large uncertainties due to differences between model physics. The inter-member CESM1-CAM5 spread is weaker (six times weaker over the Sahel), highlighting that model uncertainty is stronger than IV (figure 3(*d*)) for a 40 years averaged period. We also found this behaviour for short-term predictions (figures S4(*c*) and (*d*)).

Park *et al* (2015) and Monerie *et al* (2016b) have shown that uncertainties in simulating North Atlantic temperature change are one of the main sources of uncertainty in Sahel precipitation change. The inter-model spread in projected temperature is indeed strong over the North Atlantic Ocean (figure 3(*e*). The North Atlantic temperatures have been linked to the Atlantic Multidecadal Overturning Circulation (AMOC, Knight *et al* 2006 and Zhang and Delworth 2006), which exhibits large uncertainties in climate projections, mainly because of a strong model-dependency (Reintges *et al* 2016). The spread in surface temperature change is also strong over the Sahel, due to the spread in precipitation over land. Interestingly we found the same pattern of surface temperature inter-member spread in CESM1-CAM5 (figure 3(*f*)) as the CMIP5 inter-model spread, but with a weaker intensity (compare figures 3(*e*) and (*f*)).

3.3. Change in the seasonal cycle

In the previous section it has been shown that the western and central Sahel exhibit different responses in precipitation to climate change during JAS. Thus, we now analyse the changes of the seasonal cycle in these two regions separately (see the boxes in figure 3(*b*)). The short-term and long-term projections show similar behaviours, i.e. the decrease in precipitation over the western Sahel occurs mainly in JJA and the increase in precipitation over the central Sahel in August–September–October (ASO) (figures 4(*a*) and (*b*)). The response of the seasonal cycle in CESM1-CAM5 is also consistent with CMIP5 based studies (e.g. Biasutti 2013, Seth *et al* 2013, Kitoh *et al* 2013, Monerie *et al* 2016b). The precipitation decrease over the western Sahel in JJA has been associated with a southward shift of the monsoon system and a strengthening of the African Easterly Jet, while the precipitation increase in ASO is associated with a northward shift of the monsoon system (Monerie *et al* 2016b). During the late rainy season (September–October), the precipitation change is also partly linked to local processes including

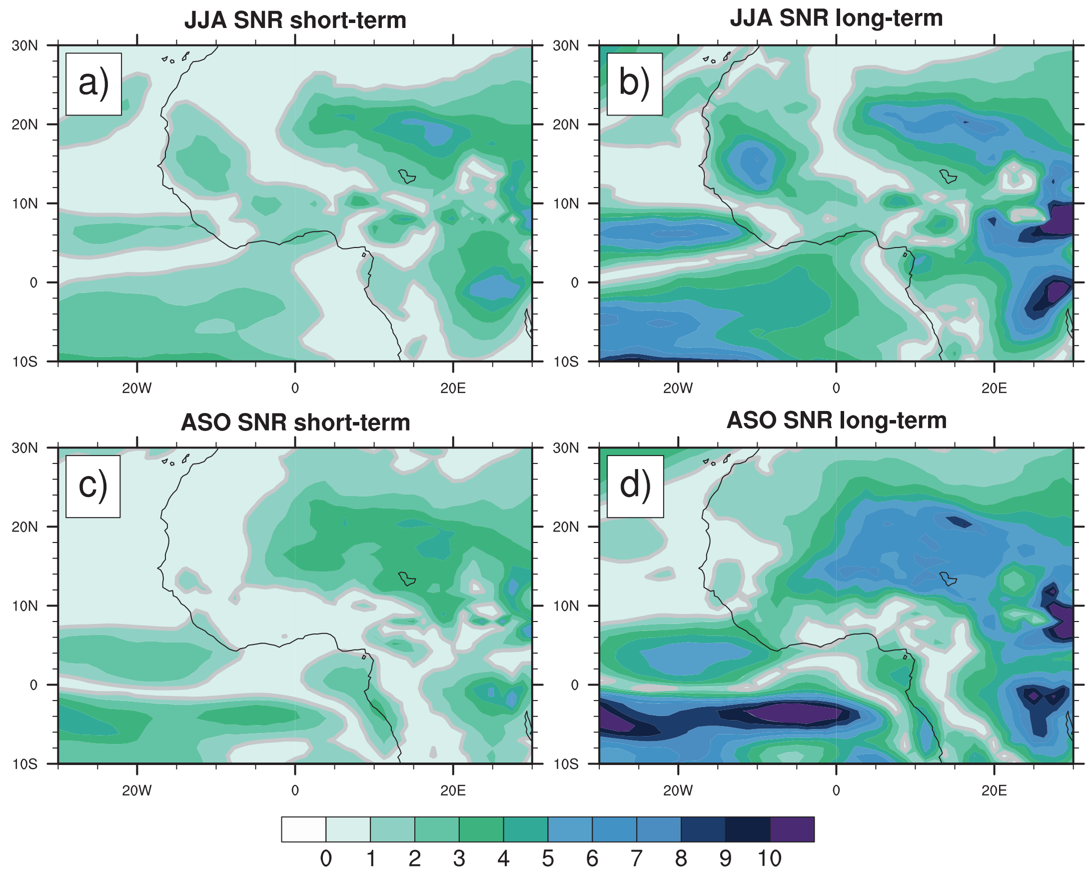

Figure 5. SNR (inter-member average divided by the inter-member standard deviation) for JJA and ASO for short term ((*a*) and (*c*); 2010–2049) and long-term ((*b*) and (*d*); 2060–2099) projections. We consider that the impact of the external forcing emerges for a SNR ≥1 (grey contour).

water recycling through soil–atmosphere coupling (Monerie *et al* 2016a). Note that, although the increase in the GHG concentration leads to qualitatively similar results at the different time-horizons, the magnitude of the long-term projected changes is stronger with larger GHG concentration changes (figures 4(*c*) and (*d*)). In order to properly assess the impacts of climate change on precipitation, we take into account these spatial (western and central) and temporal (JJA and ASO) features in our following analysis.

4. Partitioning of precipitation change into internal and externally forced components

The SNR (see section 2.2) is first computed for different time-horizons (short-term and long-term) and for both JJA and ASO. Over the central Sahel, the SNR is strong (> 2) in both JJA and ASO (figures 5(*a*) and (*b*)). In contrast, no robust signal is found to emerge over the western Sahel in ASO (figures 5(*c*) and (*d*)) for short and long-term time-horizons. As expected, the effect of anthropogenic external forcings is more robust for long-term than for short-term projections (figure 5). To investigate the contribution of IV we focus hereinafter on short-term projections, since the relative impact of IV on the precipitation change is stronger than for long-term projections. The analysis of Δpr is also focused over the western Sahel in JJA and over the central Sahel in ASO in the following sections.

The change in precipitation is decomposed into its forced and internal components (see section 2.2) for the short-term projection. The internal component has a similar magnitude as the forced response, and is different for each member, ranging from a decrease to an increase in precipitation (precipitation changes and their internal component are shown for each member in figures S5–S8). To determine how IV can obscure the forced response, we select those members exhibiting extreme behaviours over both the western and central Sahel domains. These members are shown, separately, for the western Sahel and the central Sahel, for the short-term projections in figure 6.

For the western Sahel (in JJA), member #16 exhibits a strong decrease in precipitation while member #12 exhibits a weak precipitation change (figures 6(*a*) and (*d*)). These differences between both members are purely due to IV (precipitation decreases due to IV in member #16 and increases in member #12) (figures 6(*b*) and (*e*)). Thus, IV is able to exacerbate/dampen Δpr by obscuring the forced response (which manifests as a decrease over the Western Sahel, as shown in the right panels). At the short-term time-horizon the overall effect of climate change on western

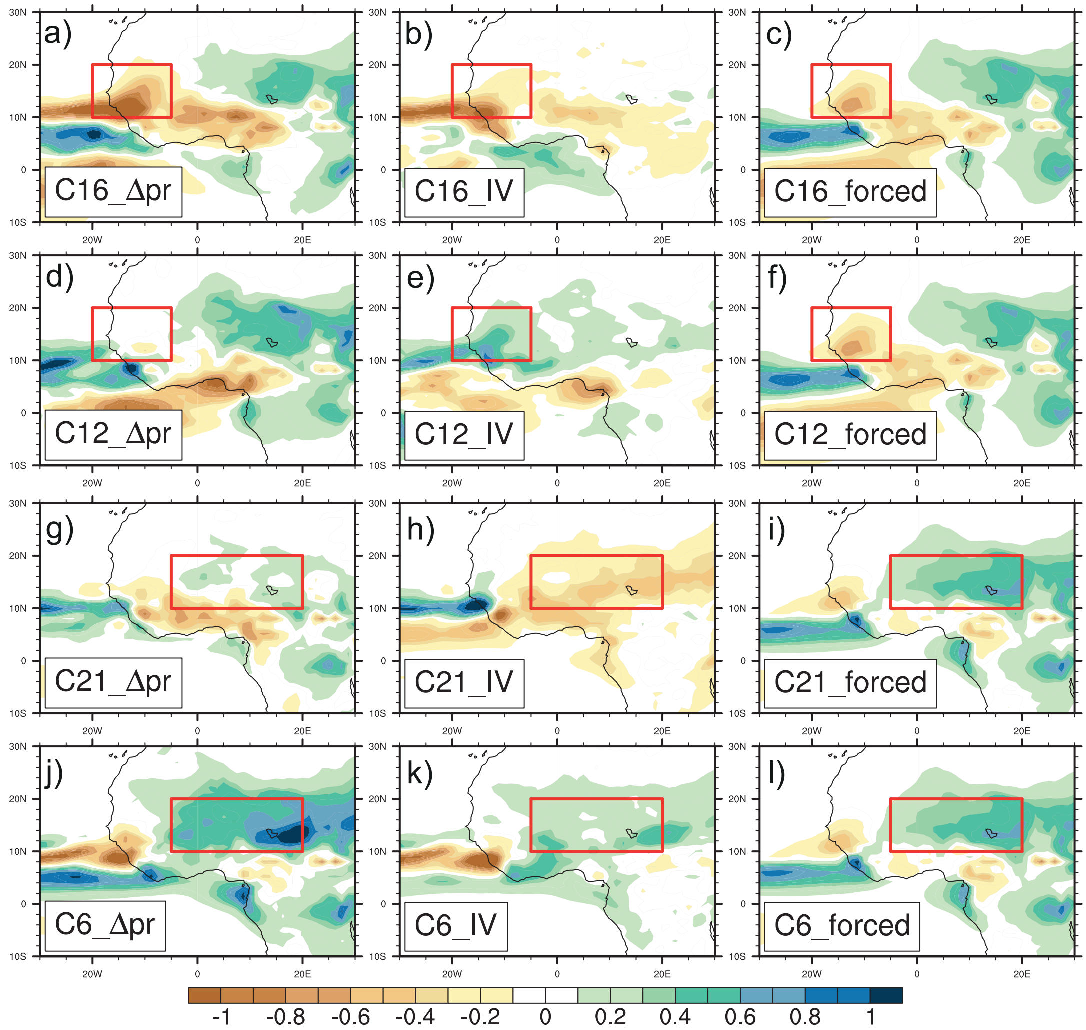

Figure 6. Projected changes (mm day^{-1}), at short-term (2010–2049) in JJA ((*a*)–(*f*)) and ASO ((*g*)–(*l*)). The internal variability (middle column) as defined from the difference between the forced response (average over all the 40 members; right column) and the individual precipitation change for an individual member (left column). The focus is on extreme cases, defined as the members for whom the precipitation change is the most different in term of sign and/or magnitude (member #16 and member #12 for the western Sahel and member #21 and member #6 for the central Sahel).

Sahel precipitation appears to be highly uncertain, and may not be the same sign as the long-term effect of the external forcing.

The same analysis is performed with a focus on the central Sahel for ASO. There, IV is also strong, leading either to a decrease (figure 6(*h*)) or an increase (figure 6(*k*)) in precipitation amounts. Yet, it does not totally offset the forced response since both ensemble members project a wetter Sahel (figures 6(*g*) and (*j*)), as also projected by the forced response (figures 6(*i*) and (*l*)).

At the longer-term time-horizon, IV is no longer able to counterbalance the forced response, since Δpr and the forced responses always have the same sign (figure S9). However, IV is still able to counterbalance/reinforce the impact of external forcings, by reducing/increasing the precipitation change over both central and western Sahel (figure S9).

The impact of IV on Sahel precipitation is strong since anomalies obtained with extreme members are outside the ensemble member spread, as computed with the 40 members (figure S10).

5. Understanding the origin of IV in climate simulations.

In this section the causes of the evolution of the precipitation anomalies (with respect to the 1960–1999 mean) over the western and the central Sahel from 2006–2100 are investigated. We estimate a time of emergence of the external signal by analysing the temporal evolution of SNR, and by understanding the contribution of internal variability versus the forced response. We analyse the interannual and decadal variability separately.

Over the central Sahel (figure 7(*b*)), the interannual IV component does increase slightly with time (consistent with Boer 2009) but for practical reasons it is considered as constant throughout time. Year-to-year impacts of the external forcing appear to be largely

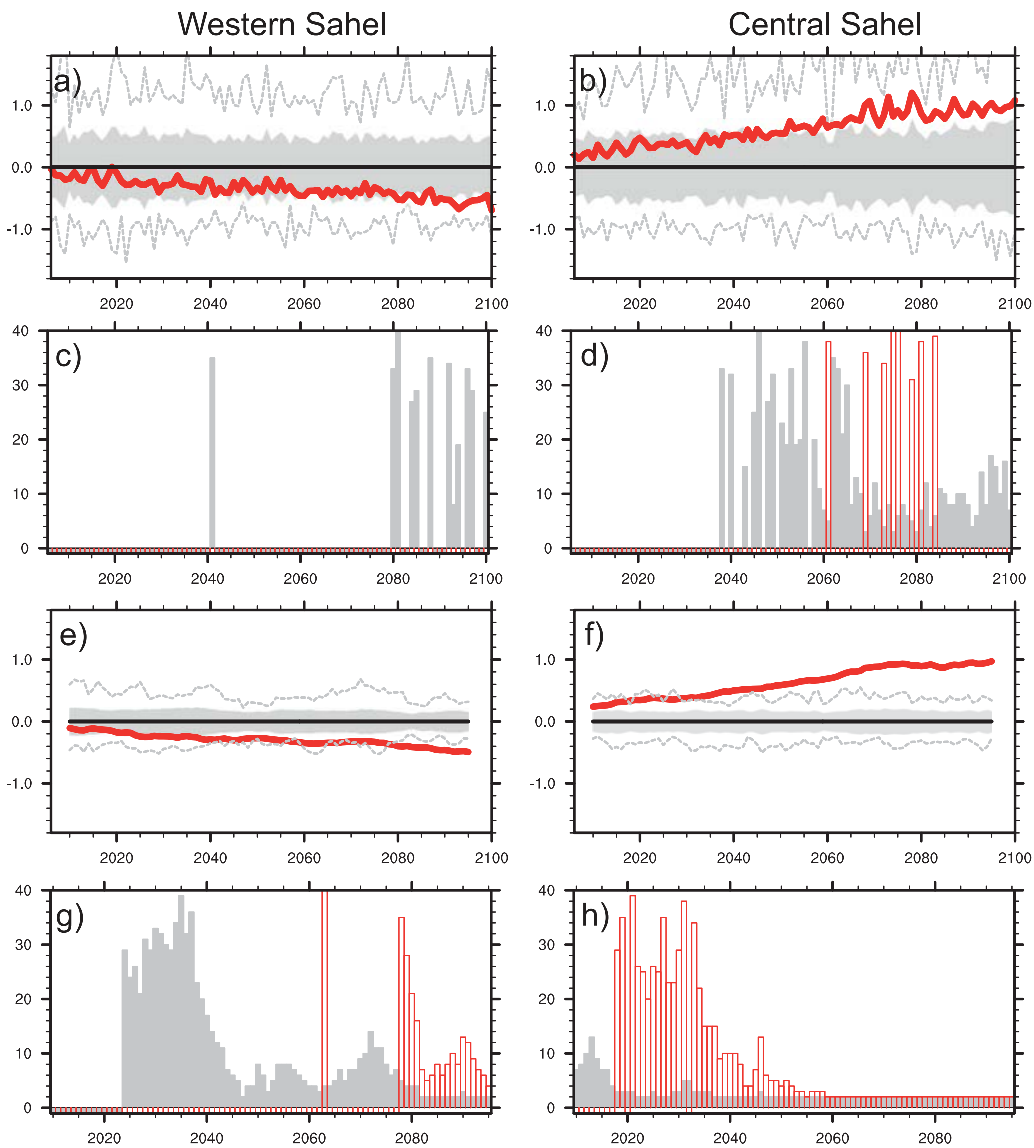

Figure 7. Precipitation change (mm day^{-1}), for each seasonal mean ((*a*) and (*b*)) and 10 year running mean ((*e*) and (*f*)). The result is given for the central Sahel over the ASO period (right column) and for the western Sahel over the JJA period (left column). The forced response (red line), the internal variability standard deviation (grey shading) and the maximum and minimum of the internal variability (i.e. the ensemble range, grey lines) are represented. We proceed by random re-sampling to define the number of members required to have 95% of chance to produce a robust precipitation change (SNR ≥ 1 and SNR ≥ 2) (the number ranges thus from 2–40; *y*-axis of the second and fourth row). We then define years (decades) for which the forced response is greater (twice) than the internal variability, i.e. the signal-to-noise ratio is greater or equal to 1 (grey bar) (greater or equal to 2; red bar) ((*c*), (*d*), (*g*) and (*h*)).

uncertain before the mid-21st century since they are weaker than the IV component. In contrast, the forced response shows a marked and continuous increase, and becomes larger than the IV component from 2060. At the end of the century each summer will be thus strongly impacted by the anthropogenic forcing, leading to a precipitation increase. IV will then be only able to obscure the forced trend in exceptionally rare cases (see the maximum and minimum values of the IV component on the figure 7(*b*)).

Over the western Sahel, the externally forced response only becomes larger than the interannual IV component at the end of the 21st century (around 2090), implying that the emerging signal due to the global warming effect is either more strongly hidden by IV and/or less strongly affected by the forced response (figure 7(*a*)). This implies a weak ability to predict precipitation change with uninitialized simulations over the western Sahel at short-term and mid-term time-horizons (2030–2069) since IV is considered as noise in CMIP simulations.

We also defined the decade for which the SNR ratio becomes larger than 1, with 40 members and after using a 10 year running mean, as also done in Deser *et al* (2012). We found homogeneous patterns over the western and central Sahel, with obtained decades consistent with figures 7(*e*) and (*f*), i.e. about 2030 over the western Sahel and before 2020 over the central Sahel (not shown).

As already shown in figure 6, precipitation changes depend on the IV simulated in each member.

Therefore, analysis based on only a few ensemble members may be biased because of sampling errors. Based on the LENS simulations, the number of members needed to obtain a detectable signal-to-noise ratio (SNR greater or equal to 1 or 2) can be calculated. To this end, we generated a set of 100 000 ensemble means and spreads from n randomly selected members (for n ranging from 2–40), that is, a total of 39 ensembles of 100 000 means and spreads. Note that the degrees of freedom is low for $n = 2$, $n = 39$ since the combinations of 2 and 39 member ensembles among 40 members is reduced. We next retain the n when 95% of the 100 000 ensembles produce a SNR greater or equal to 1 (and to 2). The minimum value of n is then considered as the minimum number of members required to obtain a robust precipitation change over the time-horizon of interest.

According to this, figures 7(*c*) and (*d*) show as a function of time, the number of members required to detect the signal from the noise (SNR > 1 or > 2). During the first half of the 21st century a robust SNR is only episodically obtained. Over the western Sahel, a detectable SNR is only reached for several and non-consecutive years (figure 7(*c*)), high SNR values (i.e. stronger or equal to 2: red bars) are not obtained. For the central Sahel a robust result (SNR ≥ 1) is obtained when using at least ten members, and only after 2060 (figure 7(*d*)).

The same analysis performed at decadal timescale, by considering 10 year running means, shows more detectable precipitation changes, since IV is smoothed (figures 7(*e*) and (*f*)). Over the central Sahel a signal is detectable in 2020 for a signal-to-noise ratio greater than 2 (figure 7(*h*)) using 30 members. However, only two to five members are needed for longer-term projection horizon from 2060 (figure 7(*g*)). In contrast, over the western Sahel at least 30 simulations are required to obtain a robust signal (SNR ≥ 1) at the short-term time-horizon, and 10 simulations for mid and long-term horizons (figure 7(*g*)). High SNR values (≥ 2) are only obtained for long-term horizon, after 2080.

6. Conclusion and discussion

The impact of climate change on Sahel precipitation remains uncertain and is strongly model-dependent (Druyan 2011, Monerie *et al* 2016b). These uncertainties are due to differences among climate models, emission scenarios and, also, to the internal variability (IV) (Hawkins and Sutton 2011). Although model response is the most prominent source of uncertainties for projections of Sahel precipitation, the IV of a given model is able to exacerbate the uncertainties, especially for short-term projections (i.e. 2010–2049). Quantifying to what extent IV may contribute to the precipitation change can lead to a better assessment of the future changes in the West African monsoon system.

In this paper we used the CESM1 Large Ensemble (40 members) to separate the simulated IV from the forced response. First we verified that the model is able to represent the intrinsic variability of the West African precipitation by comparing with observations. Next we demonstrate that the forced change in the NCAR model is representative of the CMIP5 ensemble, since it simulates a similar change in precipitation, in terms of magnitude, pattern and seasonal cycle, as other models participating in CMIP5.

We used spatially and temporarily homogeneous areas to examine the climate change impact on the Sahel (e.g. JJA over the western Sahel and ASO over the central Sahel, as shown in Biasutti 2013). The relative impact of simulated IV and its temporal evolution is highlighted by using both short-term (2010–2049) and long-term (2060–2099) time horizons. Short-term projections are strongly impacted by intrinsic climate variability (that is, IV), which is able to offset the weak, but increasing, impact of climate change. This impact on short-term projections is consistent with Hawkins and Sutton (2011) and as also with Deser *et al* (2014) for short to mid-term projections over North America. For instance, members can simulate precipitation change with the opposite sign of the low-frequency forced trend, solely due to IV. The opposite is also true, when IV trends are the same as those forced. Therefore, IV can exacerbate or reduce the impact of the climate change over the Sahel over short-term time horizons.

Deser *et al* (2012) show that the impact of climate change is not detectable when using five members. Here we focused on different seasons (JJA and ASO) and different areas (western and central Sahel) to maximize the signal-to-noise ratio. We found that precipitation changes are more robust over the central Sahel than the western Sahel, where large uncertainties due to IV prevail. In CESM1, at least 10 (30) members are needed to separate the 10 year averaged forced response from climate IV in Western Sahel for a long-term (short-term) horizon. Over the central Sahel two members (ten members) are needed for a long-term (short-term) horizon.

Understanding the relative roles of long-term forced changes compared to variability in controlling long-term trends in a region's climate is a key challenge, which has been recently highlighted by the so-called warming hiatus (Meehl *et al* 2011, Meehl *et al* 2014, Guemas *et al* 2013, Kosaka and Xie 2013, Trenberth and Fasullo 2013, Watanabe *et al* 2013). In this study we assume that the CESM1-CAM5 model is representative of the CMIP5 exercise (in terms of magnitude, pattern and seasonal cycle of the precipitation change). Furthermore, we assume that CESM1 is representative of the real world. However, CESM1-CAM5, as the other CMIP5 models, does not correctly reproduce the past variations of observed Sahel precipitation (figure 2(*a*)), and the uncertainty in projections is large (figures 3(*c*) and (*d*)). Therefore, the exact details of the projected Sahel precipitation changes, the relative importance of the internal variability to external forcing, and hence the emergence time, remains uncertain. The inability of the current models (i.e. CMIP5 and CESM1) to adequately simulate the observed variability of Sahel rainfall could be because of errors in (i) the simulation of forced variability (i.e. due to aerosols, Booth *et al* 2012 and Dong *et al* 2014), or (ii) in the simulation of low-frequency variability (see for instance Ault *et al* (2012), Ault *et al* (2013) and Biasutti (2013)), in order to quantify and understand the model uncertainty in future projections of the Sahel and, ultimately, to make more accurate predictions, further understanding of the model simulations is needed. Nevertheless, this study has shown that large ensembles (i.e. larger than was routine in CMIP5) are needed in order to adequately estimate the projected change in current models, and to be able to separate the internal variability from the forced component. Finally, given the model uncertainty, it is important that these results are confirmed with similar large ensembles performed with a different climate models.

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