

Rainfall and Drought Predictability in the Sahel on the Seasonal-Decadal Year Timescale

Written by Neil Ward (wardn626@gmail.com)

Independent consultant for the WISER programme

2019

Contents

1. Introduction: Aims and Scope
2. Existing Sahel Seasonal Forecast Capacity (lead time of 3-6 months)
3. The New “Decadal Prediction” Science
4. Potential New Product 1: extended-lead seasonal forecasts (i.e. 1-year-ahead predictions)
5. Potential New Product 2: multi-year mean forecasts (e.g. years 2-5 ahead)
6. Status and Challenges towards operationalization of the new “Decadal Prediction”
7. Other climate science issues underpinning the best application of the new forecast information
 - 7.1 Role / nature of recent trends (including spatial variation)
 - 7.2 Resolution of the contributing GCMs
 - 7.3 Eastern Sahel (especially Ethiopia) climate: aspects of Eastern Africa rainfall regimes
 - 7.4 Information on early/late season Sahel rains
 - 7.5 Rainfall versus Drought Predictability
8. Summary: Gaps and Potential Opportunities

Supported by:



Fund Manager:



1. Introduction: Aims and Scope

This report is a literature review on the topic of seasonal-decadal prediction of Sahel rainfall. It emphasizes the basis, challenges and potential for product development based on the emerging new capacity of decadal prediction. The focus is the boreal summer rainy season in the Sahel, which typically accounts for about 80% of annual rainfall in the region.

The review begins (section 2) with an overview of the now well-established seasonal prediction for Sahel rainfall with a relatively short (few months) lead time. The new “decadal prediction” science is summarized in general in section 3. Existing literature has often presented this new science in terms of a new capacity to (i) extend the lead time of existing seasonal predictions, such that they become true one-year-ahead predictions (reviewed for Sahel rainfall in section 4); (ii) provide some information about the time-mean conditions over multiple years into the future (reviewed for Sahel rainfall in section 5). Section 6 reviews the literature for status and challenges in the operationalization of the new decadal prediction capacity. Finally, section 7 provides a brief overview from the literature on some science topics relevant to the application of Sahel decadal predictions, including recent trends in the Sahel (section 7.1), spatial resolution of forecasts (7.2), some specific climate issues in the easternmost part of the target region extending into Ethiopia / Eritrea, where in some parts, rainfall is not so confined to boreal summer (7.3), the potential for information on early/late seasons rains (7.4), and literature on the question of targeted drought prediction versus rainfall prediction (7.5).

The report draws on three existing reviews which may be consulted in parallel with this report, covering the existing seasonal forecast for the Sahel (Colman et al. 2017), the interface of climate science with product development in Africa (Conway 2012) and an overview of the drivers of Sahel rainfall, with specific reference to the seasonal and decadal prediction question (Stephens and Rowell, 2018).

Supported by:



Fund Manager:



2. Existing Sahel Seasonal Forecast Capacity (lead time of a few months)

During the 1980s and 1990s, a capability was operationalized to make skillful seasonal climate forecasts for many regions including boreal summer rainfall in the Sahel. The primary source of predictability for these seasonal forecasts in the Sahel is the influence exerted by large scale sea surface temperatures (SSTs) on the boreal summer West African monsoon and associated rainfall (e.g., Lamb 1978; Folland et al. 1986, subsequent contributions including Rowell et al. 1995; Giannini et al. 2003; Rodriguez-Fonseca et al. 2015). Many parts of the global ocean play a role, including Atlantic, Pacific, Indian and Mediterranean (reviewed in Steptoe and Rowell 2018). The relation of Sahel rainfall variations with SST variations tracks both year-to-year changes in Sahel rainfall, as well as the longer-term (multi-year to a few decades) swings in Sahel rainfall. Existing seasonal forecasts can therefore track the historical longer-term variations, but the predictions are only operational with a lead time of a few months, since the operational models were only applied for typically up to 6-months ahead. For such a lead time, persistence of ocean conditions, or evolution in the near-surface component of the ocean, is sufficient to permit skillful predictions. Beyond about 6 months, the problem is more clearly linked to evolution of the ocean-atmosphere system, and requires models to be able to represent such evolutions (as is now being addressed for decadal prediction, see section 3).

Initially, the seasonal forecasts for Sahel rainfall were made by both dynamical methods as well as statistical methods, where aspects of the prevailing SST patterns were statistically related to the seasonal rainfall totals. This is reviewed in Colman et al. (2017), where it is noted that it is now largely considered that dynamical methods have over time improved to a point where they are considered more reliable than statistical methods. Dynamical methods use General Circulation Models (GCMs) of the climate system. One approach to make a forecast is to take the atmospheric part of the GCM, and drive it with the expected SST pattern for the coming few months (either assuming persistence of SST anomalies, or through explicit off-line SST prediction). Increasingly, and now predominantly, GCMs are run as fully coupled ocean-land-atmosphere models. So, to use spring climate conditions to forecast for Sahel rainfall in the summer, the following procedure may be followed: the GCM is initialized with prevailing climate conditions in say April, and run forward in time for the next 6 months, to generate climate conditions for the coming May-October

Supported by:

Fund Manager:



period. Such models can be run for past years, to explore the level of skill to expect when the system is applied operationally. Forecasts generated for past years in this way are often referred to as “hindcasts”. The illustrative set of hindcasts given in Colman et al. (2017) is reproduced here in Fig. 1a. The hindcasts correlated with the observed rainfall total with a correlation of 0.696, which is around the upper-level of skill that has been typically achieved for seasonal Sahel rainfall.

An important aspect to note in Fig. 1a, is that for a given year, multiple forecasts are presented. This is because the GCM, when starting from slightly different initial conditions, may follow a different pathway through the coming 6 months. The GCM is therefore run several times, attempting to sample the range of plausible outcomes from the existing prevailing conditions. The set of forecasts is termed the “ensemble”, and the best estimate forecast is considered as the mean of the ensemble. Hence, the correlation skill (Fig. 1a) refers to the correlation between the ensemble mean forecast and the observed. This concept inherently communicates the way in which seasonal forecasts are probabilistic in nature.

Existing seasonal forecast products may attempt to estimate the probability of different outcomes. A commonly used procedure is to work in terms of three rainfall categories, where over the historical period, the category boundaries are chosen such that each of the three categories (dry, near-normal, wet) are equally likely to occur. The forecast then estimates the probability of each category occurring in the target forecast period. This may be undertaken by direct application of the range of outcomes in the forecast ensemble, or through statistical calibration.

The optimum forecast has been shown to be achieved through the combination of the predictions of multiple prediction systems. This may be done subjectively by forecast experts (e.g., Fig. 1b) or through objective combination and calibration (e.g., Fig. 1c, see Barnston et al. 2010). Note, in Fig. 1a, the boundaries for 5 equally likely categories are given: this five-category quintile system is often used to express seasonal forecast probabilities in UK Met Office seasonal forecasts (e.g., Folland et al. 1991). Indeed, the target information may be tailored to any given application, and probabilities estimated for the target outcome (such as a specific definition of drought). These concepts have been quite widely explored now in the context of seasonal prediction (e.g., Hansen et al. 2006), and represent needed work to establish best practices for the new decadal prediction science.

Supported by:

Fund Manager:



3. The New “Decadal Prediction” Science

In the last 10-15 years, a major initiative has been to develop and evaluate predictions from GCMs for multiple years ahead (Meehl et al. 2009; Smith et al. 2013; Meehl et al. 2014). Sets of hindcasts have been run for typically at least 5-years-ahead and in some cases, up to 10-years-ahead. Evaluation approaches have often focused on skill of the hindcasts for 1-year-ahead, and skill of the mean of years 2-5 (example in Fig. 2a). Many of the experiments have been carried out in a coordinated way through the 5th phase of the Climate Model Intercomparison Project (CMIP5, Taylor et al. 2012) and the ongoing 6th phase (CMIP6, Boer et al. 2016). The hindcasts are initialized with observations of the current climate state (most important being the status of the ocean in coupled ocean-atmosphere variations), in addition to specifying changes in radiative forcing due to greenhouse gases, aerosols (both volcanic and anthropogenic), and solar variability. As with the short-lead seasonal forecasts, ensembles of an individual model are generated and averaged, and combinations of multiple models are made, although the magnitude of benefits and optimal choices of increasing ensemble size and model combination are still being explored for decadal predictions (e.g., Sienz et al. 2016).

The importance of running such hindcasts to assess potential skill is emphasized by Boer et al. (2016): *“A forecast is essentially useless unless there is some indication of its expected skill. A sequence of retrospective forecasts (known as “hindcasts”) made with a single model, or preferably multiple models, can provide historical skill measures as well as estimates of predictability”*. A caveat is provided in Smith et al. (2013): *“We also note that hindcasts do not necessarily provide an accurate estimate of forecast skill. For example, hindcasts may underestimate the skill of current forecasts, which benefit from greatly improved observations of the sub-surface ocean provided by the Argo array, but may overestimate forecast skill due to unintentional use of observations that would not have been available in a real forecast situation.”*. Nonetheless, the hindcast procedures, conducted in the coordinated framework of CMIP5 and CMIP6, are considered valuable sources of knowledge on the expected skill of decadal predictions.

Most evaluation did, in the early stages, focus on near-surface temperature (as in the examples in Fig. 2a), since temperature is considered easier to predict than precipitation (as found in the existing seasonal forecasts). A caveat is that much of the skill in temperature is achieved through tracking general warming that has

Supported by:

Fund Manager:



occurred over the hindcast set of years, with limited skill being attributable to the capture of coupled ocean-atmosphere natural fluctuations (e.g., Goddard et al. 2013). The North Atlantic is however, a window of opportunity in this respect, since it is known to exhibit particularly strong natural decadal variations (e.g., Meehl et al. 2009, Sutton et al. 2018), often measured in terms of the Atlantic Multidecadal Oscillation (AMO), an index for which is the SST averaged across much of the North Atlantic, though in recent decades, the AMO index may also be influenced by atmospheric aerosols. Skill for this index in the decadal predictions has been found to be high (e.g., Fig. 2b). This is especially relevant in terms of the potential to predict Sahel rainfall, since the AMO has been associated with decadal aspects of Sahel rainfall variation (e.g., Knight et al. 2006). Indeed, some promise for Sahel rainfall decadal prediction already emerged in early CMIP5 work evaluating precipitation in decadal predictions from multiple models (Fig. 2c) (e.g., Doblas-Reyas et al. 2013, Martin and Thorncroft 2014). This potential has now been studied in detail by Sheen et al. (2017), as highlighted in the subsequent two sections of this review.

4. Potential New Product 1: extended-lead seasonal forecasts (i.e. 1-year-ahead predictions)

Sheen et al. (2017) analyzed a set of hindcasts from the Met Office Decadal Climate Prediction system (termed DePreSys3). The hindcasts span the period from 1960 to 2014. Hindcasts have not been made for every year (or set of years), but there are sufficient to provide a good representative sample across the period 1960 to 1994 (see Figs. 3 and 4). For 1-year-ahead hindcasts, ten ensemble members were run, and the predicted values in Fig. 3 (and Fig. 4) are the ensemble average. It may be noted that the verification used GPCC gridded monthly precipitation (Schneider et al. 2014) estimated at 1-degree spatial resolution using the available stations in each year. While this dataset is respected as providing reliable best estimates of rainfall, it is limited by data availability, such that some uncertainty on the actual observed values in Fig. 3 and Fig. 4 needs to be factored into interpretation. On average, this means the skill estimates may be considered conservative estimates (especially at the small grid-box scale), actually less skill than that which would be calculated with perfect observations.

Supported by:

Fund Manager:



For rainfall averaged across the Sahel, the correlation skill is $r=0.48$ (see Fig. 3). This level of skill is somewhat lower than the short-lead seasonal forecasts (e.g., Fig. 1a), but nonetheless, is at a level with clear potential to give an early approximate indication of the upcoming Sahel rainfall season, with a lead time of 8 months. This represents a substantial advance and it is clear in Fig. 3 that the hindcasts are accurately predicting some of the major interannual Sahel rainfall variations, such as the switch from dry conditions in 1997 to wet conditions in 1998. Sheen et al. (2017) diagnose how this ability to predict year-to-year variations is linked to the model's ability to simulate variations in large-scale atmospheric stability across the Sahel, driven by SST variations that are successfully forecast as part of the model's coupled ocean-atmosphere evolution (further details also in Steptoe and Rowell, 2018).

The spatial pattern of skill (Fig. 3, left panel) suggests predictions are more accurate in the western part of the Sahel as compared to the eastern part. For the west and east Sahel boxes shown on Fig. 3 (left panel), the skill of area-averaged rainfall for west Sahel is $r=0.50$, and for east Sahel is $r=0.33$ (still estimated as statistically significant, even if less overall variance is successfully predicted).

5. Potential New Product 2: multi-year mean forecasts (e.g. years 2-5 ahead)

A further, and probably even more significant, advance in the Sheen et al. (2017) paper is the demonstrated ability of the DePreSys3 model to successfully forecast the 4-year mean Sahel rainfall with a lead time of over 1 year. For example, a model forecast initialized in November 1960 successfully forecasts the mean rainfall for 1962-1965 (as seen in the first time point of Fig. 4, right panel). These forecasts are termed “years 2-5”, and it is clear from Fig. 4 that they successfully capture the relatively wet Sahel period in the 1960s, the very dry period of the 1970s and 1980s, and the subsequent moderately wetter average conditions.

Sheen et al. (2017) explain the ability to make such multi-year forecasts primarily through moisture convergence changes: a warmer North Atlantic (as in the positive phase of the AMO) and warmer Mediterranean lead to enhanced moisture convergence and precipitation in the Sahel. The possible reasons for the ability of the model to correctly predict the relatively warmer sea-surface conditions in the North

Supported by:

Fund Manager:



Atlantic / Mediterranean in the 1960s and in the more recent epoch are discussed in Steptoe and Rowell (2018).

Skill for the “years 2-5” forecasts is quite uniformly strong across the complete Sahel (Fig. 4, left panel). When rainfall is averaged for the west and east Sahel separately, skill drops only slightly for the east Sahel ($r=0.63$) compared to the west Sahel ($r=0.75$). Since observations may be less reliable in the east Sahel, this is not considered strong evidence of spatial variation in skill, rather, the results suggest good skill across both west and east Sahel.

It is interesting to reflect that the “years 2-5” forecast has a skill for the whole Sahel ($r=0.73$) comparable to the skill of the existing short-lead seasonal forecasts (see the example in Fig. 1a). This is possible because the years 2-5 forecast is for the mean of 4 years. Making the mean can average out unpredictable year-to-year variations, so that the longer-lead 4-year mean forecast can in principle be equally or even more skillful than the short lead 1-year forecast. The value of the forecast though will depend on the user requirement. If the user is interested in exactly how the 4-year period will unfold (or drought risk in any individual year), then this product will need to be adapted and skill will be less when assessing information for each year individually within the 4-year mean. However, it is emphasized that if users are interested in the individual year risks through the 4-year period, a relatively small amount of statistical analysis of the hindcast results would enable this to be estimated. For example, the risk of a drought in one of the years in a 4-year period, or the risk of back-to-back droughts in two of the four years etc.

6. Status and Challenges towards operationalization of the new “Decadal Prediction”

Decadal prediction is an emerging capability, with ongoing exploratory experiments within the framework of CMIP6 (Boer et al 2016), as well ongoing production of what are termed “quasi-operational” forecasts, to date being undertaken primarily as a learning process (Smith et al. 2013). From 2010 to 2016, UK Met Office coordinated the exchange of quasi-real-time predictions from multiple GCMs <https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long->

Supported by:

Fund Manager:



[range/decadal-multimodel](#) (though users were advised to not base decisions on the experimental information at this stage) and UK Met Office has issued experimental information based on its own GCM system, most recently for 2018 initialized in late 2017 <https://www.metoffice.gov.uk/research/climate/seasonal-to-decadal/long-range/decadal-fc>. In September 2018, the Met Office announced that it is now the WMO Lead Centre for Annual-to-Decadal Climate Prediction responsible for collecting and providing hindcasts, forecasts and verification data from contributing centres worldwide (<http://bit.ly/2MUGJAA>). Presentation of forecasts reflects the early stage of a new product being primarily created for the science community to learn through the process, with forecasts presented simply as full anomaly fields (temperature only for UKMO released information, precipitation as well for the above-referenced multi-model exchange, and multiple variables for the new WMO Lead Centre initiative).

Some steps toward a more user-oriented operational product for a target regional like the Sahel are already in place, while other aspects appear less mature at this stage. Some observations, based on the literature and experience with the operationalization of the existing seasonal forecast are given below. They primarily address issues around the multi-year (years 2-5) product; the 1-year-ahead product is essentially a simple lead time extension of the existing seasonal forecast, though in the context of decadal prediction experiments, issues around initialization and ensemble generation are still applicable, to the extent that these are different from the existing seasonal forecast products.

(i) Hindcast Skill Assessments: The work of Sheen et al. (2017) is very strong in establishing that a decadal prediction GCM system, with given ensemble size, has the ability to perform successfully through the three substantive recent phases of Sahel rainfall. This provides strong evidence that this system can provide substantial skill, in terms of both years 2-5 and 1-year-ahead information.

(ii) Diagnose skill in the hindcasts: It increases confidence greatly if the source of skill is diagnosed (i.e. understood in terms of physical mechanisms). This has been done in Sheen et al. (2017), attributing skill to mechanisms of SST influence on the rainfall. A caveat concerns uncertainty in the literature over the relative roles of different mechanisms (returned to in section 7.1).

(iii) Real-time forecast diagnosis and evaluation: Capacity is needed to diagnose a real-time forecast, and subsequently to evaluate it, in terms of climate system

Supported by:

Fund Manager:



mechanisms as well as overall accuracy. This can be considered an important component when transitioning from quasi-operational product status.

(iv) Multi-model considerations

Introduction: The benefits (greater skill and confidence) of a multi-model approach have been firmly established for existing seasonal forecasts. In principle, the same concepts apply to decadal prediction, though in this experimental phase, there appears less literature to quantify the benefits. Nonetheless results are often presented as individual model ensemble mean skill, and multi-model ensemble mean skill, as seen in the AMO evaluation (Fig. 2b). Furthermore, it is well-known that some GCMs fail in their ability to represent Sahel rainfall variability (Colman et al. 2017). The consequence is that a simple multi-model average can be rendered substantially less accurate by inclusion of GCMs that are clearly failing.

One-year-ahead: Sheen et al. (2017) provide comparable results for other GCMs (their supplementary Table 1, reproduced here as Table 1), showing skill at 1-year-ahead and for years 2-5. The 1-year-ahead DePreSys3 skill is clearly above that of other models ($r=0.45$, compared to at best $r=0.33$, 0.32 for CanCM4 and GFDL). The multi-model mean (referred to as CMIP5 in Table 1) is lower still ($r=0.28$). Even filtering just to the significant models (CanCM4 and GFDL), it seems unlikely that a multi-model ensemble would add substantial skill at this stage.

Years 2-5: At years 2-5, Table 1 shows that MIROC5 and CanCM4 have comparable skill to DePreSys3, and other models also have statistically significant skill, suggesting potential to explore combining these skillful models (even though combining all models, CMIP5, results in a reduced skill, $r=0.54$). However, no literature has been found evaluating the mechanisms operating in the other models. At this early stage of decadal prediction, such evaluation would greatly increase confidence of adding these models into an exploratory Sahel product. Furthermore, Colman et al. (2017) also note that use of model wind fields may help in constructing multi-model information for Sahel rainfall.

Summary: The comparable skill levels shown by Sheen et al. (2017) for years 2-5 in some other GCMs are encouraging and do reinforce confidence in the DePreSys3 results. Extending to a multi-model product appears to, at this stage, still require further work.

(v) Initialization and ensemble generation. It will be important to assess that these are done in real-time in a way to support the expectation that the real-time forecasts will perform at skill levels roughly comparable to the hindcasts (under the assumption

Supported by:



Fund Manager:



that the true climate system predictability that Sheen et al extracted 1960-2014 does itself remains constant).

(vi) Detrending: All results in Sheen et al. (2017) are detrended from the early 1960s-to-present (due to model systematic drift, an issue in many decadal GCM prediction systems). Presumably there are ways to operationalize the detrending for application to a real-time forecast (this is noted in Sheen et al. though the preferred solution not discussed). One aspect to note: if hindcasts were only available 1980s to present, the detrending may potentially remove the real decadal fluctuation from 1980s to present, thus further emphasizing the value of a set of hindcasts that sample through the three phases of Sahel rainfall since 1960.

(vii) Baseline comparison with statistical approaches. When implementing GCM prediction systems, it is valuable to have a bench-mark statistical system for skill comparison. A commonly used basic system is persistence, and Sheen et al. (2017) show the improvements relative to persistence for DePreSys3 and some other CMIP5 models (Table 1). While more sophisticated statistical methods are in principle plausible, the observation of Colman et al. (2017) suggests GCMs have advanced to the point where they are preferable for existing seasonal forecasts, whereas implementation of statistical decadal prediction systems require great care due to small number of degrees of freedom in the historical data record (further discussion in Steptoe and Rowell, 2018).

(viii) Format for an experimental forecast. The literature steers toward the two new timescales of product (1-year-ahead and 2-5 year mean), however, exactly how to present the information is not found in the literature. Currently, experimental products are simply served as global anomaly fields directly output from the GCM (e.g., for surface temperature and precipitation). An experimental product for users may follow the seasonal forecast experience of presenting the 2-5 year mean Sahel rainfall forecast in terms of tercile categories. In addition, if some information is needed on the likely nature of constituent years within the 4-year period, this may be done through consultation of the ensemble of model outputs and/or through quantifying the meaning of a 2-5 year below normal tercile in terms of the mean frequency of dry years with that 4-year period. Extraction of probabilistic information is a further area for work, this may be derived through ensemble spread (Goddard et al. 2014; Lott et al. 2014; Corti et al. 2012), or adjustment based on hindcast skill (as in seasonal forecast experience, e.g., Barnston et al. 2010). Some guidance in this regard may

Supported by:

Fund Manager:



be possible by constructing forecast/observed contingency tables from sets of hindcasts such as in Figs. 3 and 4.

7. Other climate science issues underpinning the best application of the new forecast information

7.1 Role / nature of recent trends (including spatial variation)

It is widely asserted that knowledge on recent climate trends forms a valuable part of actionable climate information and product development (e.g., review in Conway 2011). This can be expected to be especially true in the application of decadal prediction for the Sahel.

Underpinning Sheen et al. (2017) is the implication that the change in rainfall from the 1960s (wet) to 1970s and 80s (dry) to the subsequent relatively wetter conditions is primarily attributable to changes in SST patterns, which they diagnose as causing changes in moisture convergence in the region. Some additional uncertainty is contributed by debate in the literature on the extent to which atmospheric composition, including aerosol loading (independent of any SST change) may contribute to Sahel rainfall changes. The exact relative role of these factors remains under debate in the literature (as noted in Steptoe and Rowell 2018, e.g., Biasutti 2013; Dong et al 2014; Dong and Sutton 2015; Janicot et al. 2015).

Taylor et al. (2017) note an increasing frequency of extreme daily rainfall events occurring in the Sahel since the 1980s, which they speculate is attributable to increased intensity of the Saharan heat low. This may represent a process missing in the Sheen et al. (2017) prediction system (hinted at in their discussion section); it does not invalidate the Sheen et al. results, but may point to an area for potential improvement (in turn, related to GCM spatial resolution, see next section).

Nicholson et al. (2018) build on work by Ali and Lebel (2009) to provide a comprehensive overview of Sahel rainfall variations from 1854 to 2014 (see Fig. 5). In addition to multi-year wet/dry phases throughout the historical record, these authors argue that Sahel rainfall underwent a regime change around 1968, moving into a drier regime, from which only partial recovery has occurred. They argue that,

Supported by:

Fund Manager:



based on the SST AMO index alone, recovery 2000-2014 should have been more complete, suggesting something else is limiting the recovery. This prompts the question whether in fact, such a process is operating in Sheen et al., such that recovery is correctly specified as only partial in the years 2-5 predictions.

Nicholson et al. (2018) also note that recovery in the eastern part of the Sahel has been stronger, although no explicit trend analyses are offered to support the assertion. While Sheen et al. (2017) report skill levels for east and west Sahel separately (with the years 2-5 skill strong in both east and west), they do not diagnose any differences in trends (or mechanisms) in the hindcasts for the two regions. This represents an area for further investigation.

The literature on recent trends therefore needs to be factored into interpretation of decadal predictions. It does not invalidate the strong decadal prediction skill found in Sheen et al. (2017) suggesting the system is capable of generating skillful predictions moving forward. But the trends literature does motivate continued diagnosis of the source of precipitation anomalies in experimental real-time decadal predictions.

7.2 Resolution of the contributing GCMs

Spatial resolution of the GCM prediction system is an important parameter influencing the features that the model can directly represent. DePreSys3 in Sheen et al. (2017) is run at 60km resolution for the atmospheric component. A relevant area of development at the Met Office is a convection permitting GCM, being run at 4km resolution (Stratton et al. 2018). This has implications for resolving of processes and potential resolution of prediction:

(i) Process: There are potential gains in model accuracy through being able to represent the interaction of the Sahara heat low with the increasing frequency of daily rainfall extremes (Taylor et al. 2017). There are also potential gains for simulating teleconnection mechanisms into the Ethiopia domain, where a high resolution model may resolve the influence of the complex orography and land/sea arrangements on regional climate patterns. It is widely reported that the Jul-Sep rains in Ethiopia are related to El Nino / Southern Oscillation (ENSO) (e.g., Koreche and Barnston 2006; Segele et al. 2015; Jury 2015) with a sign similar to the main Sahelian domain), yet GCMs have difficulty with simulating this connection (e.g., Degefu et al. 2017; Gleixner et al. 2017), which may be related to the complex orography in the Ethiopian

Supported by:

Fund Manager:



domain. Indeed one-year-ahead predictions have low skill in the vicinity of Ethiopia in Sheen et al. (2017). For 2-5 year ahead, there is some significant skill for Ethiopia (Fig. 4, left panel), but a higher resolution model may improve the representation of the trend component in such a complex orographic domain.

(ii) Forecast resolution: For initial products, regional indices, as used in Sheen et al. (2017) provide solid foundation. However, with increased model resolution, the implications of the broad scale moisture convergence changes may be amplified or diminished in the presence of small scale landscape features such as coastlines, lakes and mountains. At this stage, this is considered secondary, and the main initial potential benefit from higher model resolution may be in the mechanism improvements and associated potential increases in prediction skill, as described in (i) above.

7.3 Eastern Sahel (especially Ethiopia) climate: aspects of Eastern Africa rainfall regimes

This literature review domain extended in scope to Ethiopia and Eritrea. Parts of these areas, while experiencing important rains in Jun/Jul to Sep, also experience significant rains during Mar-May and Sep-Nov. These transition seasons connect to the broader East Africa bimodal rainfall regimes that have been widely studied at interannual and longer timescales.

Of the transition seasons, Sep-Nov is generally considered the more predictable, with a strong positive association with ENSO warm events, modulated through influence of the Indian Ocean SST (e.g., Ogallo 1988). Recently, results are also optimistic for predictability in the Feb/Mar to May period as well. For example, Fekadu (2015), used SST in statistical methods with good success for the Feb/Mar – May rains in Ethiopia. Findings are supported by Funk et al. (2014) analyzing a broad domain extending across southern Ethiopia, eastern Kenya and southern Somalia. Generally, as alluded to above for Jun-Sep, the complex orography may again be limiting GCMs performance in the transition seasons (Funk et al. 2014), so it will be a valuable opportunity to explore predictability with new high resolution GCMs experiments for the transition seasons in Ethiopia/Eritrea and surrounding areas; the statistical results encourage that a strong signal should be possible with GCMs that adequately represents the key processes.

Supported by:

Fund Manager:



There is also interest in recent multi-year variations of Feb/Mar – May/Jun rains, with a series of failures from around 1999 until recently (Funk et al. 2014; Lyon 2014; Brown et al. 2017). Such variation represents a target for validation of decadal prediction, but again the resolution issue is relevant, as evidenced by the spatial nature of the decadal change (illustrated in Fig. 6) and associated impacts (as discussed in Brown et al. 2017).

7.4 Information on early/late season Sahel rains

Forecast information about Sahel rainfall onset has long been desired by the agriculture community in particular. This has, to this point, proved mostly illusive, at least at local scales, due to local influences (e.g., Fitzpatrick et al. 2016). Encouragingly, Nicholson et al. (2018) report some consistent SST influence on Sahel rainfall in June, present across an extended analysis covering the years 1886-2014, which may serve to motivate targeted exploration of rainfall onset in both seasonal and decadal prediction; Bliefernicht et al. (2016) report ongoing work seeking to extract early and late season rains from the CFS2 GCM seasonal forecast system. In addition, Steptoe and Rowell (2018) consider robust long-term projections for seasonality changes in Sahel rainfall (systematic early and late season changes) which also may motivate exploration of such instances in seasonal-decadal predictions. However, for the moment, focus on possible operational product development for the Sahel remains focused on the core rainy season Jul-Sep.

7.5 Rainfall versus Drought Predictability

Drought monitoring and prediction has a broad community (e.g., Hao et al. 2018). Drought monitoring may focus on meteorological, hydrological or agricultural drought, which may take account of intraseasonal variations of rainfall and temperature, or direct sensing of vegetation status, for most effective detection of drought. It is still largely the case across literature that seasonal rainfall total is primarily used to infer drought severity in Sahel seasonal prediction work. A step toward more explicitly predicting meteorological drought is to use the standardized precipitation index (SPI) as a forecast target. This has been assessed in Dutra et al. (2013) for drought in African basins using ECMWF seasonal forecasts. The SPI though, is a relatively small step beyond using seasonal rainfall totals. One example of a comprehensive

Supported by:

Fund Manager:



approach to integrate monitoring and forecasting for sub-Saharan Africa (Sheffield et al. 2014) combines multiple ground data sources, remote sensing and environmental models (seasonal climate GCM, hydrology) in partnership with regional institutes in Africa. The approach combines initial land surface conditions with expectations (seasonal forecasts) of climate to infer drought risk. Experimental forecast products are available

(<http://stream.princeton.edu/AWCM/WEBPAGE/interface.php?locale=en>). For East Africa, in the context of FEWS-NET, Shukla et al. (2013) developed a more targeted system, but using similar modelling principles including land-surface models. Thus, examples exist of how to generate relatively simple drought index forecasts, or more complex drought forecasts informed by land-surface models. Potentially, decadal predictions may attempt to assess drought risks through such approaches. Indeed, while the methods of Sheffield et al. (2014) or Shukla et al. (2013) would require substantial implementation, some initial development could be achieved with a small amount of effort, translating the output of multi-year hindcasts into simple drought indices, such as SPI or water requirement satisfaction indices (WRSI), as has been widely used in monitoring contexts (such as by FEWS-NET <https://earlywarning.usgs.gov/fews/search/Africa>).

Such indices like WRSI recognize that drought impacts are sensitive to distribution of rainfall through the season (e.g., Zhang et al. 2018). An example of targeted WRSI results in the interpretation of recent trends is in Brown et al. (2017), thereby incorporating sub-seasonal distribution as well as rain/temperature/evapotranspiration. A further approach in seasonal forecast work, is to predict crop yield directly as a proxy for drought (e.g., Mishra et al. 2008). All these represent options for improvements to more explicitly move from inference from seasonal rainfall total, such as the probability of the below normal rainfall tercile (or quintile), which have been most widely used. Good progress has been made on establishing the basis for such improvements through the assessment of predictability of daily rainfall characteristics within a seasonal forecast (e.g., Moron et al. 2018 and references therein). In the multi-year context, drought prediction may also address the risk of a sequence of years below a given threshold, as an indication of multi-year drought.

Skill levels for predicting drought indices will be different from the skill levels for rainfall totals (as given in Figs. 3 and 4). Often in seasonal forecast settings, the skill levels are only modestly lower. However, a relatively small amount of work with the new decadal prediction hindcasts would be needed to confirm the way in which

Supported by:

Fund Manager:



forecast uncertainty needs to be adjusted for 4-year drought expectations (as measured by simple drought indices), compared to 4-year seasonal rainfall expectation.

8. Summary: Gaps and Potential Opportunities

Decadal prediction science has been intensively investigated in the last 10-15 years, with emerging coordination and protocols through CMIP5 and CMIP6 (Boer et al. 2016). In addition to scientific advances, the literature reports “quasi-operational” decadal predictions by various international GCM groups since about 2010. These experimental forecasts have been primarily for learning by the science community, not intended for users to base decisions upon. However, decadal hindcasts (1-year-ahead, and years 2-5) produced for the Sahel over the period from 1960 to 2014 are showing great promise, both in terms of skill and in terms of diagnosed mechanisms, such that the Sahel may represent an opportunity for an experimental, more user-driven, product.

Moving forward, some of the key gaps and opportunities that the literature review has highlighted may be summarized as follows:

Points with relevance primarily for forecast producers

i) Hindcast production and diagnosis. This is critical to establish expected levels of skill, and is substantially done over 1960-2014 for DePreSys3 GCM in Sheen et al. (2017). If there is desire to increase confidence in any real-time product through use of more than one GCM (the preferred practice in seasonal prediction), then it appears there is still a need to diagnose the other “successful” models identified in Sheen et al. (2017, supplementary material) to be confident in the mechanisms giving rise to skill, and to explore if a multi-model combination can be limited to just skillful models, or weighted by skill. However, this may not prohibit moving ahead now with an experimental prediction based solely on DePreSys3, provided other aspects below are satisfied.

ii) Need capacity to initialize and generate ensembles in real-time such that the available hindcasts can plausibly inform expected skill in real-time. This may already be the case, but is not obviously addressed in the literature (i.e. consistency of the experimental forecasts with the hindcasts needs confirmation).

Supported by:

Fund Manager:



iii) An experimental product for the Sahel would ideally require the scientist capacity to be in place to diagnose the source of any predicted anomalies (to ensure the mechanism is plausible and consistent with scientific understanding of Sahel rainfall). In addition, it is good practice to have capacity to validate the forecast, both for accuracy, and ideally in this experimental phase, in terms of mechanisms that gave rise to the observed anomaly. Given the product is potentially years 2-5, this implies a commitment on the part of the producer.

Points requiring interaction between producers and users

iv) Initial assessment of the possible format of a simple experimental product, such as a prediction of the likelihood of years 2-5 mean rainfall terciles (analogous to a seasonal forecast generic product). However, extraction of probabilistic information for decadal predictions requires assessment (mature in seasonal forecasts, which may provide insights). In addition, the spatial scale of the forecast needs assessment; for example, the regional indices assessed for whole Sahel, and east/west Sahel (as in Sheen et al. 2017) provide solid foundation. Development to national scale may involve national meteorological expertise, including for validation of model hindcasts / experimental real-time forecasts and stakeholder interaction. This also has implications for capacity at national level meteorology services, where discussion may consider the extent to which this may be a relatively efficient addition to the existing capacity for the currently operational short-lead seasonal forecast.

v) Assess if and how to design best recent climate information products to enhance value of decadal predictions (e.g., graphical presentation of trends and mean anomalies (respect to long-period averages) for e.g., the last 10-years, the last 30-years; does forecast continue recent trends etc.).

vi) Explore more tailored forecast formats, such as translation into the risk of drought as measured by drought indices, both for the 4-year period combined, or broken out into the risk of an extreme drought year within the 4-year period, or sequences of back-to-back droughts in the 4-year period etc.

Science Issues

vii) Some science issues potentially leading to quick improvement and extension of products: Potential improvements through the application of a higher resolution GCM have been noted, motivating diagnosis of such experiments. For the easternmost part of the Sahel region (especially Ethiopia and Eritrea), large gains may be possible

Supported by:

Fund Manager:



with the high resolution model, as well as exploring rains outside the Jul-Sep window, which in easternmost areas can be substantial. Indeed, recent multi-year variations in Mar-May in this region (which extends southward into Eastern Africa more generally) may form natural targets to explore for decadal predictability, given they have been diagnosed as related to SST in the literature.

Supported by:



Fund Manager:



References (the subset included in the text)

- Barnston, A. G., Li, S., Mason, S. J., DeWitt, D. G., Goddard, L., & Gong, X. (2010). Verification of the first 11 years of IRI's seasonal climate forecasts. *Journal of Applied Meteorology and Climatology*, 49(3), 493-520.
- Biasutti, M. (2013). Forced Sahel rainfall trends in the CMIP5 archive. *Journal of Geophysical Research: Atmospheres*, 118(4), 1613-1623.
- Bliefernicht, J., Siegmund, J., Seidel, J., Arnold, H., Waongo, M., Laux, P., & Kunstmann, H. (2016). *Forecasting droughts in West Africa: Operational practice and refined seasonal precipitation forecasts*. Paper presented at the EGU General Assembly Conference Abstracts.
- Boer, G. J., Smith, D. M., Cassou, C., Doblas-Reyes, F., Danabasoglu, G., Kirtman, B., . . . Msadek, R. (2016). The decadal climate prediction project (DCPP) contribution to CMIP6. *Geoscientific Model Development*, 9(10), 3751.
- Brown, M. E., Funk, C., Pedreros, D., Korecha, D., Lemma, M., Rowland, J., . . . Verdin, J. (2017). A climate trend analysis of Ethiopia: examining subseasonal climate impacts on crops and pasture conditions. *Climatic change*, 142(1-2), 169-182.
- Colman, A., Rowell, D., Foamouhoue, A. K., Ndiaye, O., Rodríguez-Fonseca, B., Suarez, R., . . . Diop-Kane, M. (2017). Seasonal Forecasting. *Meteorology of Tropical West Africa: The Forecasters' Handbook*, 289-322.
- Conway, D. (2011). Adapting climate research for development in Africa. *Wiley Interdisciplinary Reviews: Climate Change*, 2(3), 428-450.
- Corti, S., Weisheimer, A., Palmer, T., Doblas-Reyes, F., & Magnusson, L. (2012). Reliability of decadal predictions. *Geophysical Research Letters*, 39(21).
- Degefu, M. A., Rowell, D. P., & Bewket, W. (2017). Teleconnections between Ethiopian rainfall variability and global SSTs: observations and methods for model evaluation. *Meteorology and Atmospheric Physics*, 129(2), 173-186.
- Doblas-Reyes, F., Andreu-Burillo, I., Chikamoto, Y., García-Serrano, J., Guemas, V., Kimoto, M., . . . Van Oldenborgh, G. (2013). Initialized near-term regional climate change prediction. *Nature Communications*, 4, 1715.
- Dong, B., & Sutton, R. (2015). Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nature Climate Change*, 5(8), 757.
- Dong, B., Sutton, R. T., Highwood, E., & Wilcox, L. (2014). The impacts of European and Asian anthropogenic sulfur dioxide emissions on Sahel rainfall. *Journal of Climate*, 27(18), 7000-7017.
- Dutra, E., Giuseppe, F. D., Wetterhall, F., & Pappenberger, F. (2013). Seasonal forecasts of droughts in African basins using the Standardized Precipitation Index. *Hydrology and Earth System Sciences*, 17(6), 2359-2373.

- Fekadu, K. (2015). Ethiopian seasonal rainfall variability and prediction using canonical correlation analysis (CCA). *Earth Sci*, 4(3), 112-119.
- Fitzpatrick, R. G., Bain, C. L., Knippertz, P., Marsham, J. H., & Parker, D. J. (2016). On what scale can we predict the agronomic onset of the West African Monsoon? *Monthly Weather Review*, 144(4), 1571-1589.
- Folland, C., Owen, J., Ward, M. N., & Colman, A. (1991). Prediction of seasonal rainfall in the Sahel region using empirical and dynamical methods. *Journal of Forecasting*, 10(1-2), 21-56.
- Folland, C. K., Palmer, T. N., & Parker, D. E. (1986). Sahel rainfall and worldwide sea temperatures, 1901–85. *Nature*, 320(6063), 602.
- Funk, C., Hoell, A., Shukla, S., Blade, I., Liebmann, B., Roberts, J. B., . . . Husak, G. (2014). Predicting East African spring droughts using Pacific and Indian Ocean sea surface temperature indices. *Hydrology and Earth System Sciences*, 18(12), 4965.
- Giannini, A., Saravanan, R., & Chang, P. (2003). Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, 302(5647), 1027-1030.
- Gleixner, S., Keenlyside, N. S., Demissie, T. D., Counillon, F., Wang, Y., & Viste, E. (2017). Seasonal predictability of Kiremt rainfall in coupled general circulation models. *Environmental Research Letters*, 12(11), 114016.
- Goddard, L., Kumar, A., Solomon, A., Smith, D., Boer, G., Gonzalez, P., . . . Mason, S. J. (2013). A verification framework for interannual-to-decadal predictions experiments. *Climate Dynamics*, 40(1-2), 245-272.
- Hansen, J. W., Challinor, A., Ines, A., Wheeler, T., & Moron, V. (2006). Translating climate forecasts into agricultural terms: advances and challenges. *Climate Research*, 33(1), 27-41.
- Hao, Z., Singh, V. P., & Xia, Y. (2018). Seasonal drought prediction: advances, challenges, and future prospects. *Reviews of Geophysics*.
- Janicot, S., Gaetani, M., Hourdin, F., Giannini, A., Biasutti, M., Mohino, E., . . . Salack, S. (2015). The recent partial recovery in Sahel rainfall: a fingerprint of greenhouse gases forcing. *GEWEX News*, 27, 11-14.
- Jury, M. R. (2015). Maritime continent winter circulation as a predictor of El Nio-Southern Oscillation (ENSO) influence on Ethiopia summer rainfall. *Scientific Research and Essays*, 10(17), 559-569.
- Knight, J. R., Folland, C. K., & Scaife, A. A. (2006). Climate impacts of the Atlantic multidecadal oscillation. *Geophysical Research Letters*, 33(17).
- Korecha, D., & Barnston, A. G. (2007). predictability of June–September rainfall in Ethiopia. *Monthly Weather Review*, 135(2), 628-650.
- Lamb, P. J. (1978). Large-scale tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. *Tellus*, 30(3), 240-251.

Supported by:

Fund Manager:



- Lebel, T., & Ali, A. (2009). Recent trends in the Central and Western Sahel rainfall regime (1990–2007). *Journal of hydrology*, 375(1-2), 52-64.
- Lott, F. C., Gordon, M., Graham, R. J., Scaife, A. A., & Vellinga, M. (2014). Reliability of African climate prediction and attribution across timescales. *Environmental Research Letters*, 9(10), 104017.
- Lyon, B. (2014). Seasonal drought in the Greater Horn of Africa and its recent increase during the March–May long rains. *Journal of Climate*, 27(21), 7953-7975.
- Martin, E., & Thorncroft, C. (2014). Sahel rainfall in multimodel CMIP5 decadal hindcasts. *Geophysical Research Letters*, 41(6), 2169-2175.
- Meehl, G. A., Goddard, L., Boer, G., Burgman, R., Branstator, G., Cassou, C., . . . Hawkins, E. (2014). Decadal climate prediction: an update from the trenches. *Bulletin of the American Meteorological Society*, 95(2), 243-267.
- Meehl, G. A., Goddard, L., Murphy, J., Stouffer, R. J., Boer, G., Danabasoglu, G., . . . Hawkins, E. (2009). Decadal prediction: can it be skillful? *Bulletin of the American Meteorological Society*, 90(10), 1467-1485.
- Mishra, A., Hansen, J. W., Dingkuhn, M., Baron, C., Traoré, S. B., Ndiaye, O., & Ward, M. N. (2008). Sorghum yield prediction from seasonal rainfall forecasts in Burkina Faso. *Agricultural and forest meteorology*, 148(11), 1798-1814.
- Moron, V., Robertson, A. W., & Wang, L. (2018). Weather within Climate: Sub-seasonal predictability of tropical daily rainfall characteristics.
- Nicholson, S. E., Fink, A. H., & Funk, C. (2018). Assessing recovery and change in West Africa's rainfall regime from a 161-year record. *International Journal of Climatology*, 1-17.
- Ogalo, L. (1988). Relationships between seasonal rainfall in East Africa and the Southern Oscillation. *International Journal of Climatology*, 8(1), 31-43.
- Rodríguez-Fonseca, B., Mohino, E., Mechoso, C. R., Caminade, C., Biasutti, M., Gaetani, M., . . . Xue, Y. (2015). Variability and predictability of West African droughts: A review on the role of sea surface temperature anomalies. *Journal of Climate*, 28(10), 4034-4060.
- Rowell, D. P., Folland, C. K., Maskell, K., & Ward, M. N. (1995). Variability of summer rainfall over tropical North Africa (1906–92): Observations and modelling. *Quarterly Journal of the Royal Meteorological Society*, 121(523), 669-704.
- Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Ziese, M., & Rudolf, B. (2014). GPCC's new land surface precipitation climatology based on quality-controlled in situ data and its role in quantifying the global water cycle. *Theoretical and Applied Climatology*, 115(1-2), 15-40.
- Segele, Z. T., Richman, M. B., Leslie, L. M., & Lamb, P. J. (2015). Seasonal-to-interannual variability of ethiopia/horn of Africa monsoon. Part II: Statistical

- multimodel ensemble rainfall predictions. *Journal of Climate*, 28(9), 3511-3536.
- Sheen, K., Smith, D., Dunstone, N., Eade, R., Rowell, D., & Vellinga, M. (2017). Skilful prediction of Sahel summer rainfall on inter-annual and multi-year timescales. *Nature Communications*, 8, 14966.
- Sheffield, J., Wood, E. F., Chaney, N., Guan, K., Sadri, S., Yuan, X., . . . Demuth, S. (2014). A drought monitoring and forecasting system for sub-Saharan African water resources and food security. *Bulletin of the American Meteorological Society*, 95(6), 861-882.
- Shukla, S., McNally, A., Husak, G., & Funk, C. (2014). A seasonal agricultural drought forecast system for food-insecure regions of East Africa. *Hydrology and Earth System Sciences*, 18(10), 3907-3921.
- Sienz, F., Müller, W. A., & Pohlmann, H. (2016). Ensemble size impact on the decadal predictive skill assessment. *Meteorologische Zeitschrift*, 25, 645-655.
- Smith, D. M., Scaife, A. A., Boer, G. J., Caian, M., Doblas-Reyes, F. J., Guemas, V., . . . Ho, C. K. (2013). Real-time multi-model decadal climate predictions. *Climate Dynamics*, 41(11-12), 2875-2888.
- Stephens, H., & Rowell, D. (2018). *Sahel rainfall analysis for DFID Sudan: Review of Climate Outlook*. Met Office Hadley Centre.
- Stratton, R. A., Senior, C. A., Vosper, S. B., Folwell, S. S., Boutle, I. A., Earnshaw, P. D., . . . Manners, J. (2018). A pan-Africa convection-permitting regional climate simulation with the Met Office Unified Model: CP4-Africa. *Journal of Climate*(2018).
- Sutton, R., McCarthy, G., Robson, J., Sinha, B., Archibald, A., & Gray, L. (2018). Atlantic Multi-decadal Variability and the UK ACSIS programme. *Bulletin of the American Meteorological Society*(2018), 415-425.
- Taylor, C. M., Belušić, D., Guichard, F., Parker, D. J., Vischel, T., Bock, O., . . . Panthou, G. (2017). Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, 544(7651), 475.
- Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, 93(4), 485-498.
- Zhang, W., Brandt, M., Tong, X., Tian, Q., & Fensholt, R. (2018). Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel. *Biogeosciences*, 15(1), 319.

Supported by:

Fund Manager:



TABLES

TABLE 1: From Sheen et al. (2017, supplementary material), introducing the discussion of skill across different models for the interannual and multi-year information, and comparisons to persistence skill.

Supplementary Table 1 Correlations between de-trended observed Sahel precipitation and various CMIP5 initialized model outputs¹. Values are computed for the Sahel box and the West and East Sahel (delineated by 10°E). Start years are as in DePreSys3, but only up to 2009 (the end of the CMIP5 hindcasts), such that values are slightly different to Fig. 1. Models analysed are all initialized: CanCM4, GFDL, MPI and MIROC5 have January start dates, other models have November start dates (i.e. 2 months earlier). Results are from a 10 member model mean, other than MPI and MIROC5, with 3 and 6 members, respectively. For the multi-model mean, differences in ensemble size are accounted for by bootstrapping - the 49 CMIP5 members are randomly re-sampled to 5000 ten-member sub-sets and compared with different combinations of the DePreSys3 ten members (resampled with replacement). c denotes a significantly higher correlation than climatology (i.e. $r = 0$) at the 90% level. d means that DePreSys3 has significantly higher correlation at the 90% level. Persistence skill is also included, computed by persisting the observed average over the equivalent number of summer seasons for the period prior to each model initialisation date.

	Low frequency variability (lead-times: 2–5 yrs)			Inter-annual variability (lead-times: 1 yr)		
	Whole Sahel	West Sahel	East Sahel	Whole Sahel	West Sahel	East Sahel
DePreSys3	0.70c	0.71c	0.62c	0.45c	0.48c	0.29c
CMIP5	0.54c	0.54c	0.42c	0.28c	0.29c	0.20
DePreSys1A ²	0.44	0.55c	0.18d	0.11d	0.11d	0.04d
DePreSys1F ²	0.64c	0.67c	0.51c	0.17d	0.13d	0.23
CanCM4 ³	0.69c	0.64c	0.59c	0.32c	0.39c	0.21
GFDL ⁴	0.54c	0.61c	0.34	0.33c	0.38c	0.22
MPI ⁵	0.15	0.19d	0.08	0.25	0.26	0.22
MIROC5 ⁶	0.70c	0.63c	0.66c	0.21	0.17	0.19
Persistence	0.50	0.49	0.40	0.21	0.34	0.03

Supported by:



Fund Manager:



FIGURES

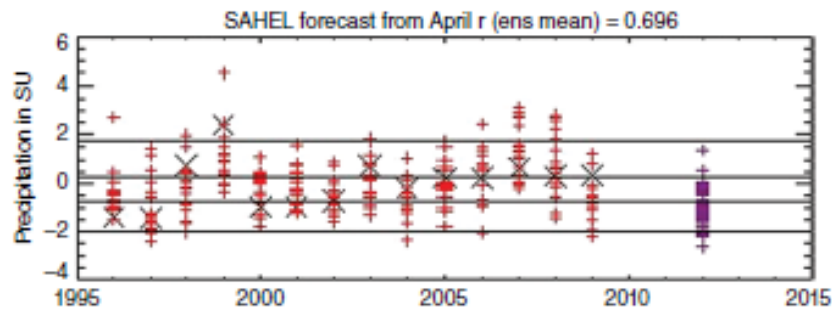


Fig. 1a. Dynamical predictions from the Met Office GloSea4 system initialised in April for the July-September Sahel rainfall. *Source:* Met Office. © Crown Copyright. As shown in the review by Colman et al. (2017).

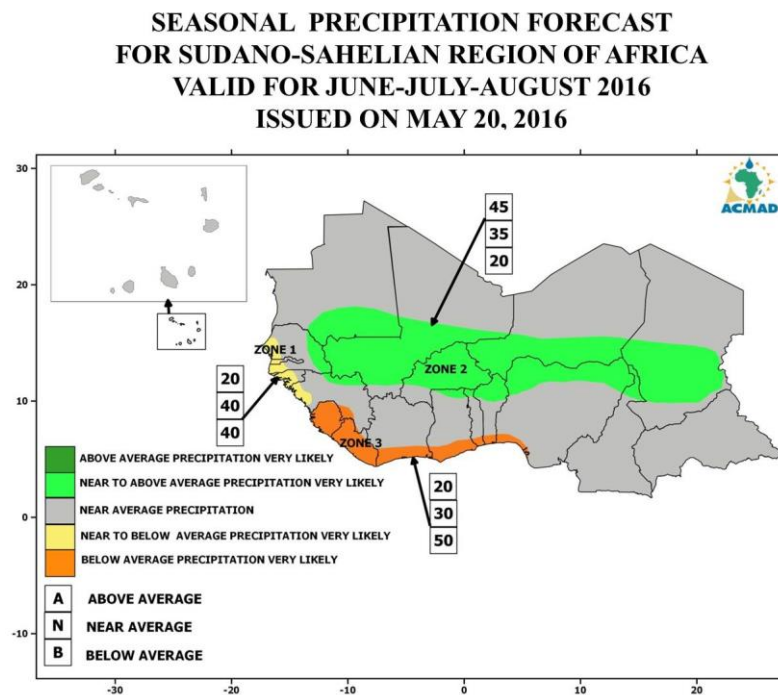


Fig. 1b. Example of operational seasonal forecast probabilities of the tercile category (given in the three boxes), along with color-coded presentation of the forecast with clarifying worded communication. <http://acmad.net/rcc/presao.php>.

Supported by:



Fund Manager:



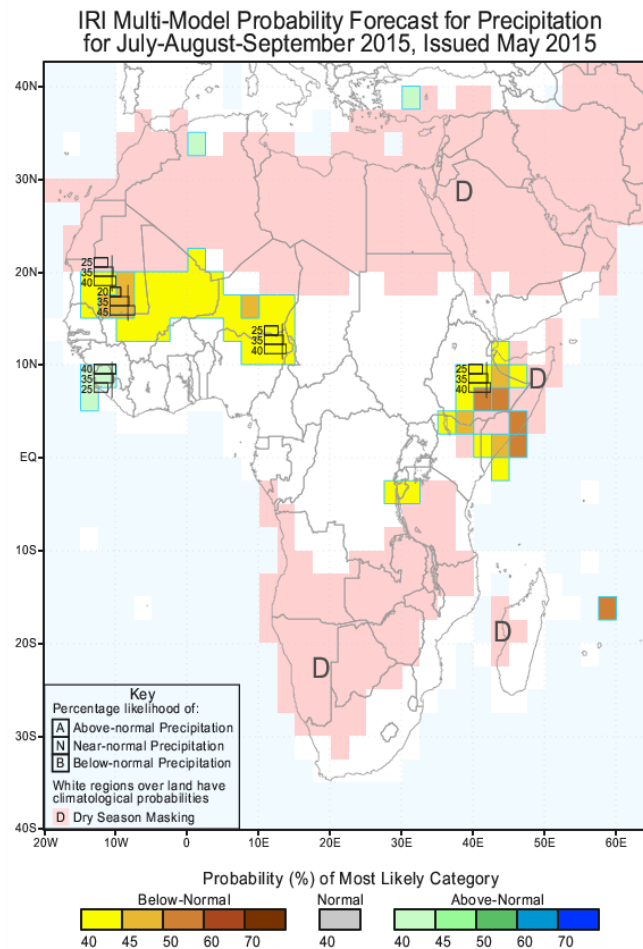


Fig. 1c. Example of operational multi-model combination and calibration for forecast of tercile category. Barnston et al. (2010) provide discussion of methods underpinning this product.

<https://iri.columbia.edu/our-expertise/climate/forecasts/seasonal-climate-forecasts/>

Supported by:



Fund Manager:



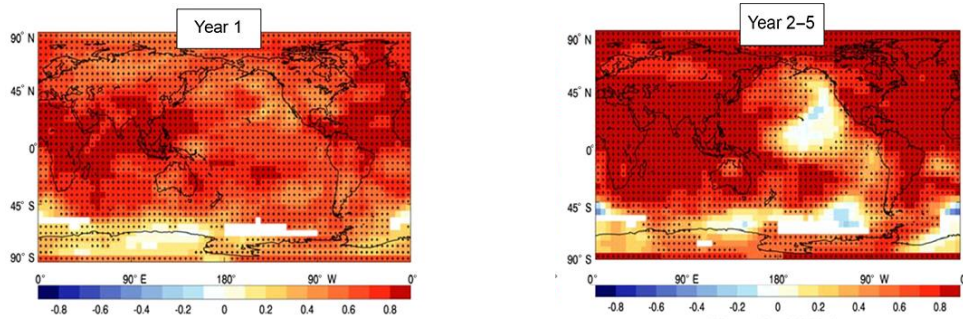


Fig. 2a. Example of the evaluation of Decadal Prediction Experiments. Correlation skill for Year 1 and Year 2-5 forecasts of surface air temperature, based on averaging the results from different models: CanCM4, GFDL, MPI-ESL-LR, MIROC5, HadCM3 and the HadCM3 PPE hindcasts. Stippling denotes that the results are significant at the 10% level (using a two-tailed test). As shown in Boer et al. 2016.

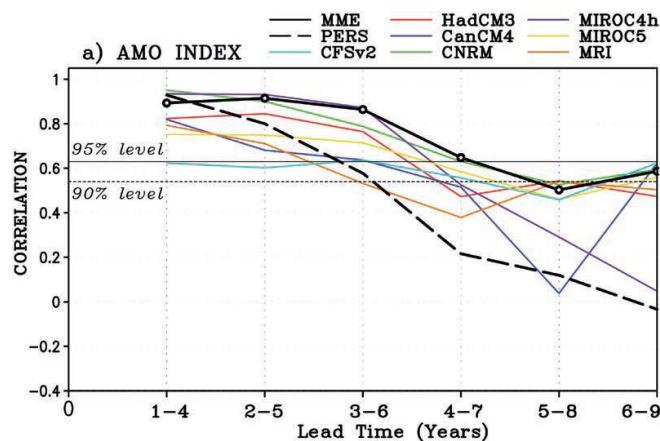


Fig. 2b. Correlation skill for the AMO index computed from seven models from the CMIP5 multi-model ensemble. Correlations are calculated from the time series obtained by averaging hindcasts and model results for various prediction times (e.g., 1-4 years, 2-5 years, etc.). High correlations indicate better predictive skill, and are generally better for prediction time periods closer to the initial time (e.g., predictions for years 1-4 are generally better than for those for years 6-9). Each model is represented by a colored line, the multi-model ensemble is the solid black line, and persistence (taking the initial state and persisting it in time) is the dashed black line. The solid and dashed horizontal lines represent significance at the 95% and 90% levels, respectively (Kim et al. 2012). As shown in Meehl et al. 2014.

Supported by:

Fund Manager:



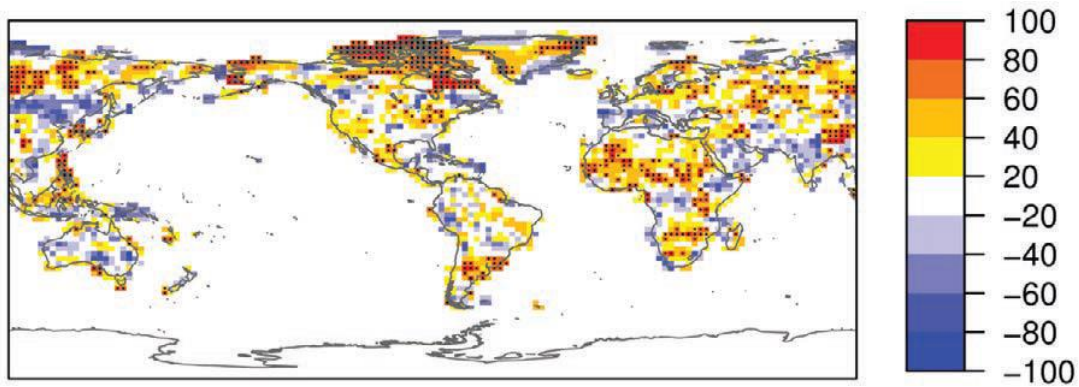


Fig. 2c. Precipitation predictive skill (correlation with observations, *100), predictions for years 6–9 averages based on CMIP5 multi-model ensemble mean hindcasts. Results are from initialized hindcasts with 5-yr intervals between start dates from 1960 to 2005. Correlations are calculated by averaging all the hindcasts from all the models for each start date for the 6–9-yr hindcasts. Stippling indicates significance at the 95% level (Doblas-Reyes et al. 2013). As shown in Meehl et al. 2014.

Supported by:



Fund Manager:



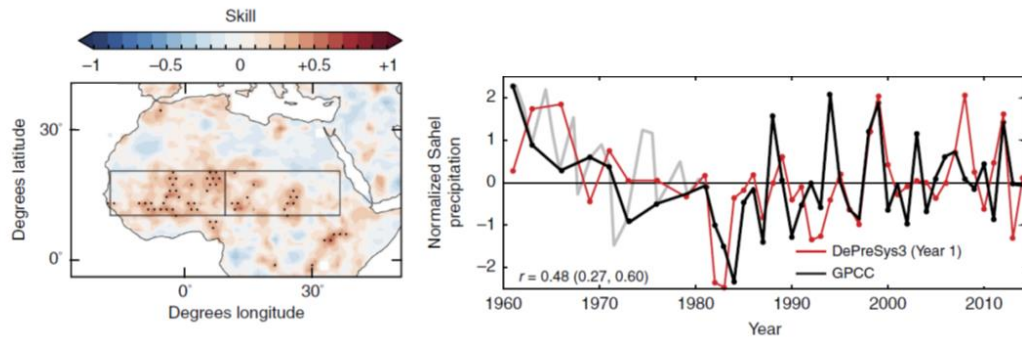


Fig. 3. Skill of Sahel rainfall predictions, 1-year-ahead seasonal forecast. Model is initialized in November, to forecast the following year's July-September Sahel rainfall. Left panel shows the correlation skill at each grid-box (stippled is significant at the 95% level). Right panel shows the predicted and observed rainfall averaged across the Sahel region. Note that prior to 1980, experiments are run only for selected years (for information, where a forecast is not run, the observed rainfall value is still shown in light gray). From Sheen et al. (2017)

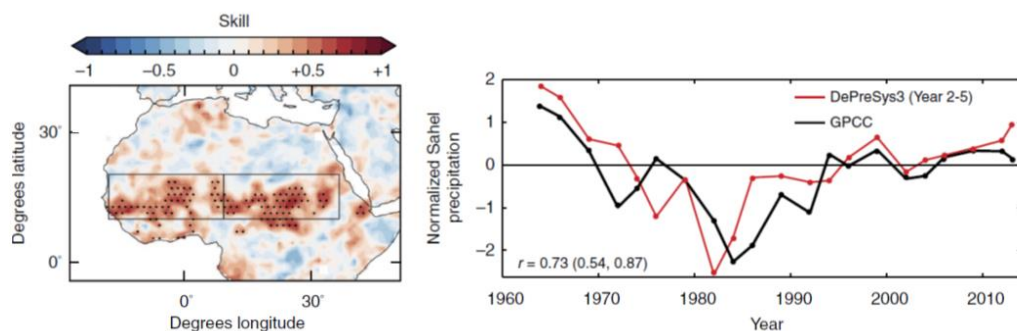


Fig. 4. Skill of Sahel rainfall predictions, Year 2-5 mean rainfall (e.g. model is initialized in Nov 1960, predicts the mean July-September Sahel rainfall for the years 1962-1965). Left panel shows the correlation skill at each grid-box (stippled is significant at the 95% level). Right panel shows the predicted and observed rainfall averaged across the Sahel region. From Sheen et al. (2017).

Supported by:



Fund Manager:



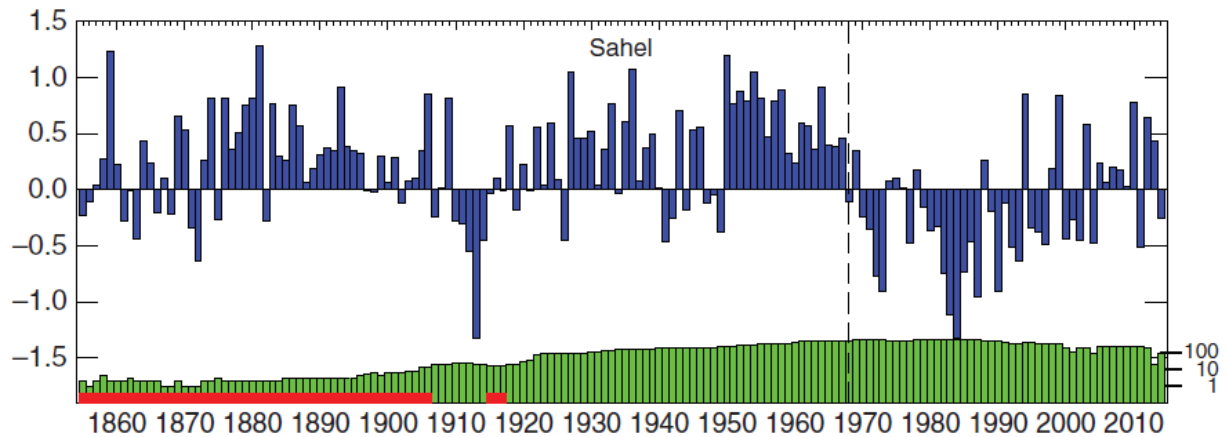


Fig. 5. Time series of Sahel rainfall from 1854 to 2014. Rainfall is represented by a regionally averaged standardized departure from the long-term mean (i.e., the total record length for each station). A value of 1 is equivalent to one standard deviation. The dashed vertical line indicates the year 1968. The number of stations in the average is indicated at the bottom in green. From Nicholson et al. (2018). (The years indicated in red along the x-axis are those to which a scaling factor was applied due to small number of contributing stations).

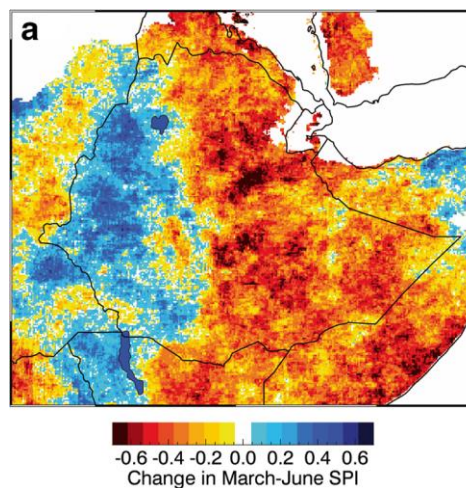


Fig. 6. March–June 1999–2014 changes in standardized seasonal precipitation (SPI) (relative to earlier epoch) based on the CHIRPS rainfall dataset. The map shows the changes across Ethiopia and surrounding locations. Areas with climatological mean rainfall of less than 50 mm were removed from the analysis. From Brown et al. (2017).

Supported by:

Fund Manager:

