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Key Points:
- First decadal climate predictions made starting from 1901
- Inclusion of few more cycles of decadal variability for skill estimation
- First prediction of the 1920s North Atlantic climate transition and impact

Supporting Information:
- Readme
- Figure S1
- Figure S2

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Decadal climate predictions for the period 1901–2010 with a coupled climate model

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Abstract An ensemble of yearly initialized decadal predictions is performed with the Max Planck Institute Earth System Model to examine the forecast skill for the period from 1901 to 2010. Compared to the more recent period (1960 to present day), the extended period leads to an enlargement of regions with significant anomaly correlation coefficients (ACC) for predicted surface temperatures. This arises from an increased contribution of the trend, which is also found in the uninitialized runs. Additionally, in the North Atlantic decadal variability plays a larger role over the extended period, with detrended time series showing higher ACC for the extended compared to the short period. Furthermore, in contrast to the uninitialized simulations, the initialized predictions capture the North Atlantic warming events during the 1920s and 1990s, together with some of the surface climate impacts including warm European summer temperatures and a northward shift of Atlantic tropical rainfall.

1. Introduction

Initialization of coupled climate models from near observational states has been shown to improve decadal climate predictions [*Smith et al*., 2007; *Keenlyside et al*., 2008; *Pohlmann et al*., 2009]. In the fifth coupled model intercomparison project (CMIP5) improved skill is particularly found in the North Atlantic and Pacific [*Doblas-Reyes et al*., 2013]. However, these previous assessments are restricted by observations and reanalyses which cover the period from 1960 to the present day. Given the short period, the skill assessment considers only a small number of cycles of the observed decadal to multidecadal variability and is furthermore strongly affected by the trend. This is illustrated in Figure 1, which shows that North Atlantic sea surface temperature (SST) variability is dominated by the trend for the period since 1960, as considered by the CMIP5 protocol. However, variability around the trend becomes more important over longer periods. This can have an effect on the forecast skill estimation. Here we initialize the coupled Max Planck Institute Earth System Model (MPI-ESM) with a recently developed ocean estimate (W. A. Müller *et al*., A 20th-century reanalysis forced ocean model to reconstruct North Atlantic multidecadal climate variability from 1872–2010, submitted to *Climate Dynamics*, 2014), and for the first time, assess the forecast skill of a set of retrospective predictions covering an extended period from 1901 to 2010.

Skill assessments for current forecasts systems identify the North Atlantic as a key region for decadal climate predictions [e.g., *Pohlmann et al*., 2009; *Smith et al*., 2010; *van Oldenborgh et al*., 2012; *Matei et al*., 2012]. Predictability is found for integrated quantities such as the Atlantic Meridional Overturning circulation [*Pohlmann et al*., 2013] or the subpolar gyre (SPG) [*Matei et al*., 2012; *Yeager et al*., 2012; *Robson et al*., 2013a]. Furthermore, the North Atlantic SST and heat content exhibit prediction skill for up to 10 years [e.g., *Kröger et al*., 2012; *Matei et al*., 2012; *Yeager et al*., 2012]. Prediction skill is also assessed for climate impacts in the North Atlantic, including tropical cyclones [*Smith et al.,* 2010; *Dunstone et al.,* 2011] and seasonal means of European temperatures [*Müller et al*., 2012].

However, over the relatively short period considered in previous studies, North Atlantic hydrographic records exhibit only one cycle of the observed decadal to multidecadal variability. For example, SST in the SPG region shows a strong transition from a relatively cold period prior to the mid-1990s to a warm period afterward. This transition had an important impact on surface climate [*Sutton and Dong*, 2012] and is related to prolonged phases of a strong North Atlantic Oscillation (NAO) and associated heat transports [*Robson et al*., 2012]. By initialization of a coupled climate model, it is further shown that such events are predictable a couple of years ahead [*Robson et al*., 2013a; *Yeager et al*., 2012].

On the other hand, hydrographic records exhibit additional historical phase transitions such as the 1920s climate variation during which the North Atlantic switched from cold and fresh conditions prior to the 1920s

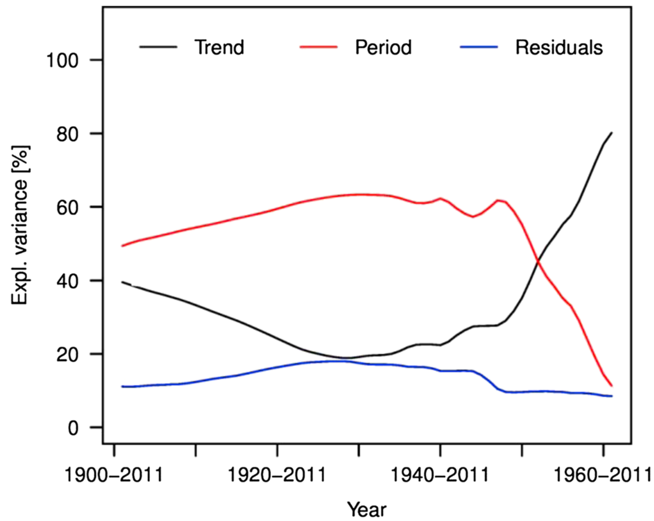

Figure 1. The explained variances of (black) trend, (red) periodic component, and (blue) residual for yearly mean HadISST averaged for the North Atlantic region (80°W–10°W, 20°N–60°N) in dependence of different lengths of the analyzed time period (e.g., 1900–2010, 1910–2010,…). The explained variances are achieved by linear regression analysis. The explanatory variable of the trend is the global CO_2 evolution and the periodic component consists of sinus and cosine series with an optimal period of 67 years. The optimal period is determined by performing multiple regressions with periods from 5 to 100 years and maximizing the total variance explained.

to warm and saline conditions from the 1930s to the 1960s [e.g., *Polyakov et al.,* 2010]. Most ocean reanalyses only cover the period since the 1960s because subsurface ocean observations before that are very sparse. However, some attempts have been made to reconstruct the ocean state prior to the 1960s [*Giese et al.*, 2010; *Lee et al.*, 2011; Müller *et al.*, submitted manuscript, 2014], by forcing ocean models with the twentieth century reanalysis (20CR) [*Compo et al.*, 2011]. Müller *et al.* (submitted manuscript, 2014) forced the Max Planck Institute ocean model (MPIOM) with 20CR to simulate the observed decadal to multidecadal variability in the North Atlantic. In these experiments, the 1920s climate variation is reasonably reconstructed by the ocean model and, similar to the 1990s, the increase of SST results from prolonged NAO-like forcing and associated northward heat transport prior to the climate variation.

However, no previous attempt has been made to use these extended ocean reanalyses to assess decadal predictions before the 1960s. Here we apply the reconstructed ocean estimates from the MPI ocean model to perform a set of assimilation and retrospective prediction experiments covering the period 1901–2010. In the next section, the experiments are described in more detail. We then focus on the prediction skill for surface temperatures (section 3) and the impact of the 1920s climate variation on the surface climate (section 4). Conclusions and discussion are given in section 5.

2. Data and Methods

The coupled model MPI-ESM is used to perform historical runs (uninitialized) and retrospective decadal prediction (initialized) experiments for the period 1901–2010. The experiments are performed in a low-resolution configuration (MPI-ESM-LR) with the latest version of the ocean model MPIOM [*Jungclaus et al.*, 2013] and the atmospheric component ECHAM6 [*Stevens et al.*, 2013]. The ocean model is run with a horizontal resolution of 1.5° on average and 40 vertical levels. For ECHAM6 the horizontal resolution is T63 with 47 vertical levels including the upper stratosphere up to 0.1 hPa.

A total of three ensemble members each of uninitialized and initialized experiments are performed. The uninitialized experiments are started from a preindustrial control simulation and forced with aerosol and greenhouse gas concentrations for the period 1850–2005 and the RCP4.5 scenario thereafter, together with observed solar variability and volcanic eruptions. The initial conditions for the initialized runs are taken from assimilation experiments using the coupled model. In these, the model state is nudged toward three-dimensional daily ocean temperature and salinity anomalies, which are added to the model climatology. Temperature and salinity anomalies are taken from MPIOM experiments [Müller *et al*., submitted manuscript, 2014] forced with individual members of the National Oceanic and Atmospheric Administration/National Centers for Environmental Prediction twentieth century reanalysis (20CR) [*Compo et al.*, 2011]. No assimilation of atmospheric parameters is applied. Three-dimensional atmospheric and ocean fields of the assimilation experiments are taken as initial conditions. The hindcasts are started yearly on 1 January and have a length of 10 years.

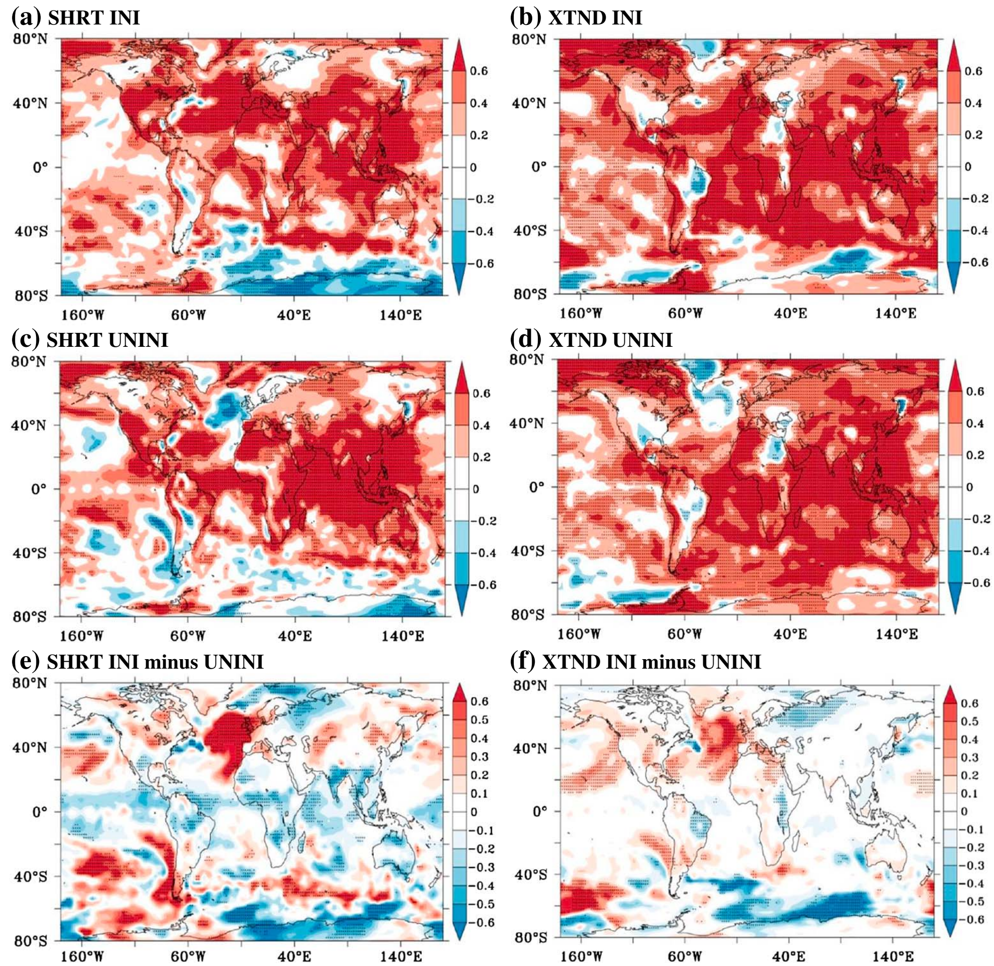

Figure 2. Anomaly correlation coefficients for surface temperature for SHRT (1960–2010) and XTND (1901–2010). The coefficients show the correlation of (a, b) ensemble mean year 2–5 predictions against ensemble mean 20CR, (c, d) ensemble mean uninitialized against ensemble mean 20CR, and (e, f) differences between ensemble mean year 2–5 predictions and uninitialized. Stippled areas indicate significant values at a 95% confidence level.

We assess skill over the extended period 1901–2010 (XTND) and the short period 1960–2010 (SHRT). For each period, simulated and observed anomalies are defined relative to their respective climatology. For the uninitialized runs, the climatology is calculated from their ensemble mean. Anomalies of initialized runs are defined with respect to the climatology of the ensemble mean and lead time. Here a "leave-one-out" cross validation is applied, such that the considered prediction does not appear in the climatology [*Gangstø et al.*, 2012]. The trend of the observations and model data is removed at each grid point by a fit of the respective data to the global mean temperature [*Trenberth and Shea*, 2006]. The trends are calculated for each period individually.

The predictions are verified against the twentieth century reanalysis, for which global data are available for the considered period. Predictions of surface temperatures are also verified against Hadley Centre/Climate Research Unit East Anglia surface temperature (HadCRUTv3) [*Brohan et al.,* 2006] and Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) [*Rayner et al.,* 2003], but the results do not differ with respects to 20CR (not shown). The predictions are assessed using anomaly correlation coefficients (ACC) and root-mean-squared error (RMSE) [*Wilks* 2011]. The significances of the correlations are assessed via bootstrap method. The serial correlation of the time series is taken into account by resampling in blocks of the observations, where the block length is defined by their *e*-folding times. For this paper we show results for the ensemble means.

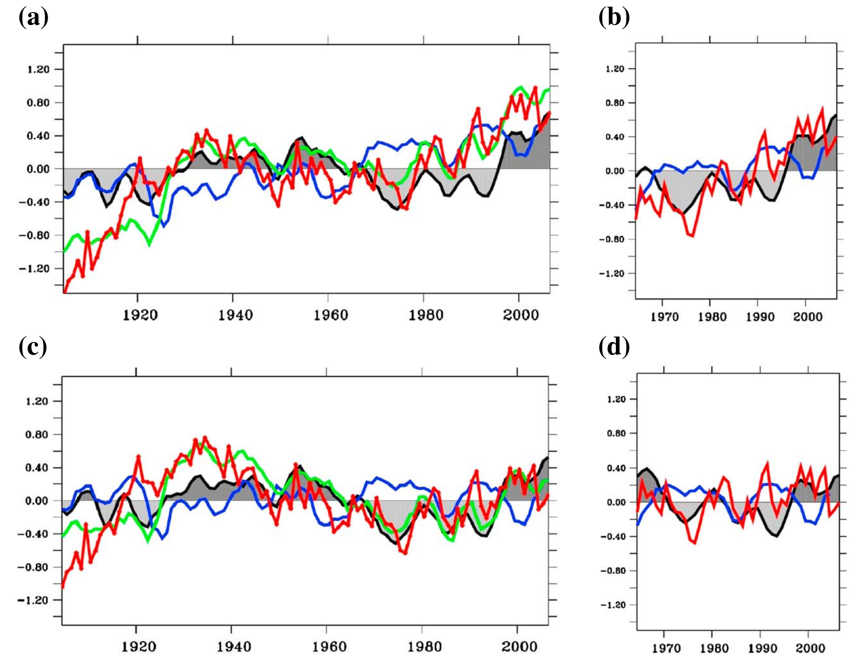

Figure 3. Running 4 year mean sea surface temperature anomalies for the North Atlantic (80°W–10°W, 40°N–60°N) for (a) XTND and (b) SHRT. Shown are ensemble means of 20CR (black), assimilation (green), retrospective predictions year 2–5 (red), and uninitialized runs (blue). Units are in °C. (c, d) Same as Figures 3a and 3b but for detrended time series.

3. Prediction of Surface Temperatures for the Period 1901–2010

First, we show maps of the ACC of 4 year running mean surface temperatures for the initialized (years 2–5) and uninitialized runs for SHRT and XTND (Figure 2). For SHRT, the initialized experiments show significantly higher ACCs than the uninitialized simulations in the extratropical North Atlantic and regions within the North and South Pacific (Figures 2a, 2c, and 2e), consistent with previous studies [*Müller et al*., 2012; *Doblas-Reyes et al*., 2013]. Within the tropical Pacific the ACCs are low which is a common feature in many prediction systems [*Kim et al.*, 2012]. Compared to previous decadal predictions of MPI-ESM performed for the CMIP5, however, the ACCs are considerably larger (not shown). In many regions the ACC of the uninitialized runs is of similar magnitude to the initialized runs, indicating that much of the significant correlation results from the trend (Figure 2c).

For XTND, the ACCs are increased in many regions in the initialized runs and show larger areas of significant values compared to SHRT, particularly between ~ 40°N and ~40°S (Figure 2b). This result from a larger contribution of the trend in XTND is compared to SHRT, since the ACC is also increased in the uninitialized runs (Figure 2d). In addition, in large parts of the North Atlantic, the ACCs of the initialized runs are significant for XTND and are similar to SHRT (Figures 2a and 2b). Further, in the uninitialized runs the ACCs are higher in XTND than in SHRT, where in SHRT large negative values prevail (Figures 2c and 2d). Although for both periods, significant positive forecast skills are found in this region. However, the skill in SHRT is larger than in XTND, which also stems from the negative correlations in the SHRT uninitialized runs (Figures 2e and 2f).

Furthermore, for the North Atlantic a stronger contribution to the forecast skill can also be expected from the multidecadal variability in XTND, as suggested in Figure 1. Also, detrended correlation maps (Figure S1 in the supporting information) show a clear improvement in XTND relative to SHRT in the North Atlantic. To examine this further, we present time series of North Atlantic SST in the 20CR and our hindcast and calculate the corresponding ACC and RMSE when the trend is included and removed (Figures 3 and 4). The time series show that pronounced climate variations are present during the 1920s, 1960s, and 1990s and are accompanied by phases of positive and negative temperature anomalies (Figure 3). The assimilation experiments capture the observed multidecadal variability, confirming the applicability of the ocean data prior to the 1960s. However, the assimilated and initialized SST anomalies exhibit a stronger trend than the

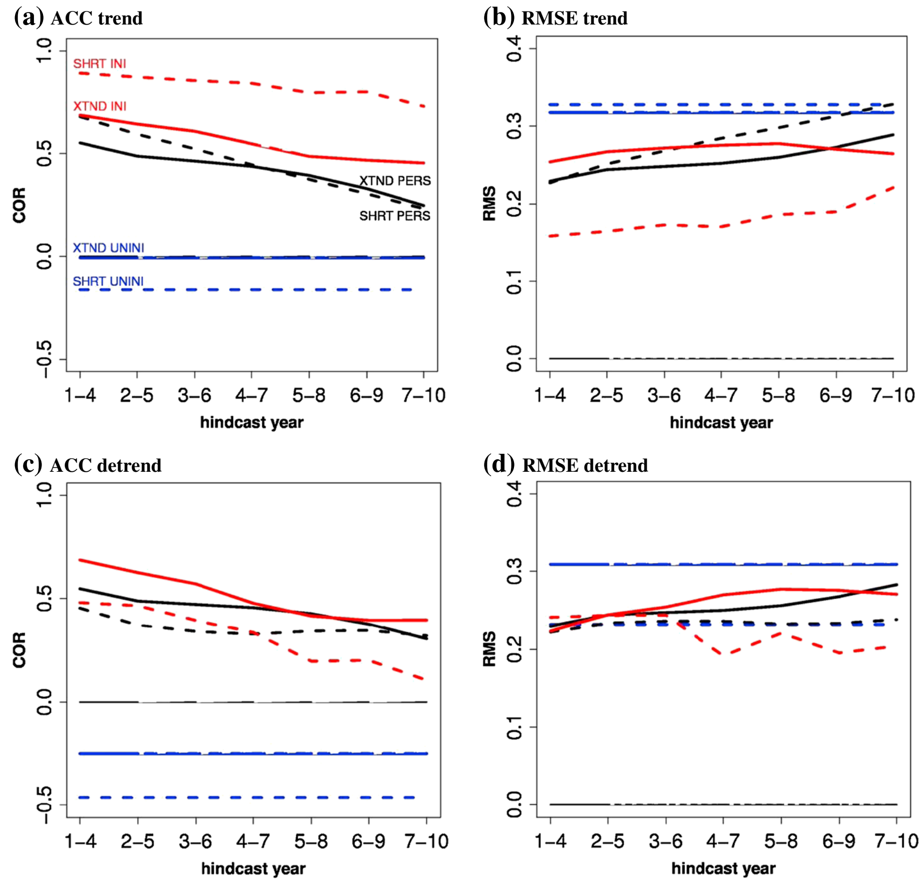

Figure 4. Anomaly correlation coefficients for SSTa averaged within the North Atlantic region for (a) trend included and (c) detrended time series. Shown are coefficients of correlation of 20CR with predictions year 2–5 (red), persistence forecasts (black), and uninitialized runs (blue). Dashed lines show results for SHRT and solid lines show results for XTND. (b, d) Same as Figures 4a and 4c but for the root-mean-squared error. Units are in °C.

reanalysis (Figure 3a) and have large negative temperature anomalies during the first two decades of the experiments, which are due to a strong cooling of the North Atlantic of the forced ocean model in the first decades [see also Müller *et al*., submitted manuscript, 2014]. Here the forced ocean model and subsequently the assimilation runs exhibit a strong intrusion of Arctic freshwater into the North Atlantic, leading to cooler and fresher water masses particularly in the SPG region until the 1910s. In particular, the initialized runs capture the increase in SST during the 1920s and 1990s, the cooling during the 1960s, and the prolonged positive and negative phases in between. However, the uninitialized experiments do not capture these observed multidecadal phases.

The time series of the initialized runs are closer to observations in SHRT than in XTND during the period since 1960 (Figures 3a and 3b). However, this may be because bias correction minimizes errors over the shorter time period and may not reflect improved forecast skill. Indeed, time series for which the trends are removed indicate a closer match to the observed multidecadal variability in XTND compared to SHRT (Figures 3c and 3d). This is reflected in higher detrended correlations in XTND compared to SHRT (Figure 4c), although RMSEs are larger because the variability during the 1920s and 1930s is overestimated (Figure 4d). For almost all lead times, the detrended correlations in XTND are higher than persistence.

In summary, in many regions the skill is improved in XTND because the trend has a larger impact relative to the variability. However, in the North Atlantic the correlations in SHRT are artificially high because they are dominated by an increase which appears as a trend in this short period but is clearly variable when a longer period is considered. In this region the skill is improved in XTND but only after detrending.

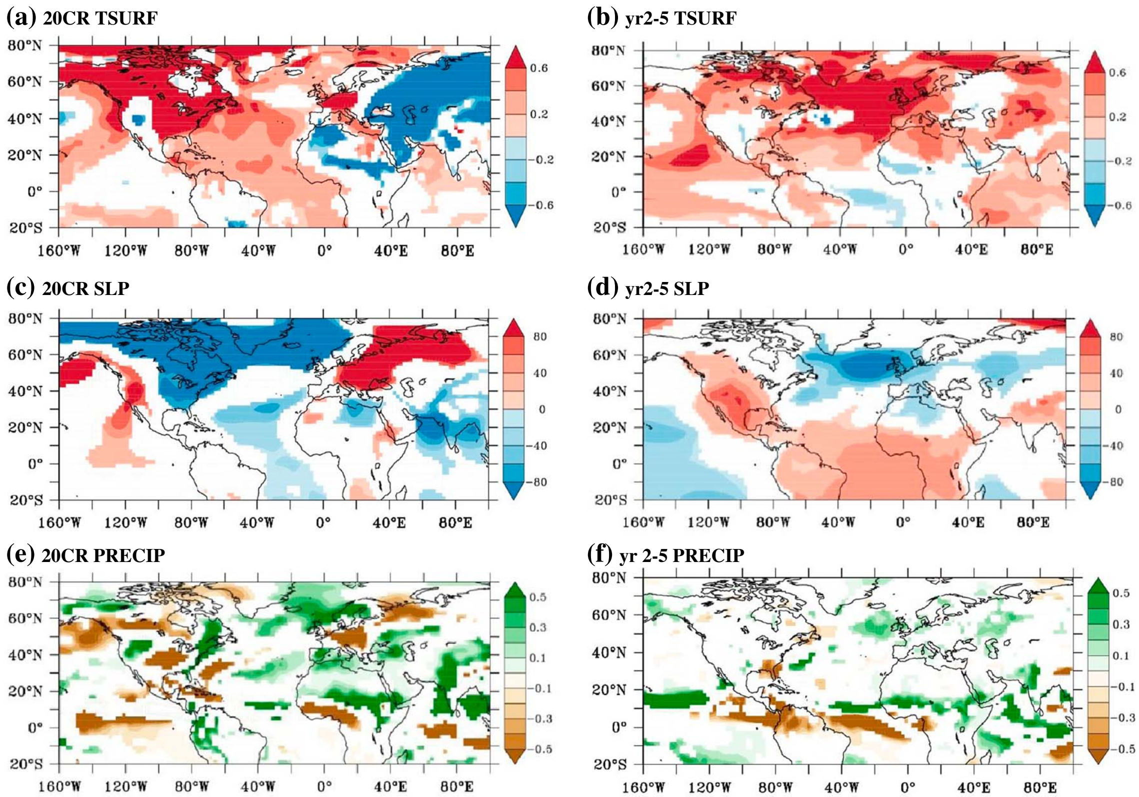

Figure 5. Composites of summer (JJA) surface temperature anomalies for the period 1930–1945 minus 1905–1920 for (a) ensemble mean 20CR and (b) predictions year 2–5 minus uninitialized. Units are in °C. (c–f) Similar to Figures 5a and 5b but for sea level pressure and precipitation, respectively. Units are in Pascal and mm/day. Colors indicate significance with p values < 0.1.

4. Prediction of the 1920s Surface Climate Changes

The previous section has shown that the climate variations in the North Atlantic SSTs during the 1920s and 1990s are captured by the initialized runs. Since these climate variations are outstanding in magnitudes and have a strong impact on the observed surface climates [e.g., *Sutton and Dong*, 2012], it is important to investigate to what extent the prediction system can capture the impact of the climate shifts. For the 1990s variation, such an approach has been applied by *Robson et al.* [2013b]. With the Met Office decadal prediction system (DePreSys), they demonstrated that the observed changes in various surface climate variables over the North American and European regions are predictable beyond the first year. In the following, we investigate the climate impacts following the North Atlantic climate variation during the 1920s. Since seasonal differences are important for the impacts [*Hodson et al*., 2010; *Sutton and Dong*, 2012; *Robson et al*., 2013a], we assess the climate impacts for the seasonal means. We focus on the summer season (June-July-August) since the North Atlantic European surface climate is closely linked to the Atlantic Multidecadal Oscillation [*Hodson et al.,* 2010; *Bladé et al*., 2011], and for this season forecast skill has been detected for the current model system [*Müller et al.,* 2012].

To assess the impact of the 1920s climate variation, 16 year means for the periods before and after the 1920s are considered. Here we calculate the temperature difference of the periods 1930–1945 minus 1905–1920. The temperature differences in the reanalysis follow the 1920s climate variation and are similar to those after the 1990s, such as the increase of North Atlantic SST and Western European surface temperature and a cooling of the African tropics (Figures 5a and S2a, see also *Robson et al.* [2013b, Figure 4b]). Some differences occur, such as the warming over North America, for which signs are reversed compared to the 1990s climate variation. Moreover, the cooling over Asia appears much stronger during the 1920s than during the 1990s.

There are also some similarities in precipitation and sea level pressure (SLP) in the two periods. For precipitation, there is a northward shift of the Intertropical Convergence Zone (ITCZ) and an increase in northern Europe and associated dryness in central to Eastern Europe. SLP shows a low-pressure anomaly over the subtropical and extratropical Atlantic in both cases. However, the overall SLP structures are not compatible, such as the prevailing negative NAO anomaly during the 1990s and a North-West to South-East pressure gradient during the 1920s. Also other regions show dissimilarities within the two cases.

Following *Robson et al.* [2013b] the impact of the initialization is assessed by looking at the difference of the initialized to the uninitialized runs. The pattern of the predicted summer mean differences is similar to the observations, such as the increase of temperatures over Western Europe and Northern America and the decrease over Eastern Europe, tropical Africa, and southwestern U.S. (Figure 5b). Further similarities are present in the Pacific with negative values in the Tropics and positive anomalies in the subtropics. However, over the tropical Atlantic, the initialized runs show a cooling rather than a warming. The magnitudes of the anomalies also deviate from observations, such as the predicted increase of SST in the SPG region and Eurasian and North American surface temperature. Such an effect is also seen in the CMIP5 prediction system, for which the predicted SST and its remote response deviate from observations as a result of the inherent model dynamics [*Müller et al.,* 2012]. Moreover, the current experiments are based on a forced ocean model, which has a bias toward a fresh and cold state prior to the 1920s (see also Figure 3a). Consequently, the predicted SLP favors a negative anomaly over the eastern SPG region (Figure 5d) and associated predicted precipitation differs from observations (Figure 5f). Interestingly, the shift of the Atlantic ITCZ is predicted for the 1920s and 1990s variation.

5. Conclusions and Discussion

We have presented the forecast skill of an ensemble of yearly initialized retrospective predictions performed with the MPI-ESM covering the period 1901–2010. The predictions show similar forecast skill in regions of the North Atlantic and Pacific Ocean as in other climate prediction systems [*Doblas-Reyes et al.,* 2013]. In contrast to these prediction systems, which consider the period 1960 to the present day, the extended period improves the robustness of the results.

We find an enlargement of significant regions of the anomaly correlation in both the initialized and uninitialized runs. This is generally because here the trend plays a larger role relative to the variability particular over the extended period. Removing the trend leads to a strong reduction of anomaly correlations, though forecast skill remains significant for regions such as the North Atlantic. Moreover, detrended time series reveal higher ACCs in the North Atlantic over the longer period compared to the shorter period. This is a result of the inclusion of additional phases of the multidecadal variability, which includes prolonged periods of negative and positive temperature anomalies, for example, prior to and after the 1920s climate variation. For the short period since 1960, the prediction skill in the North Atlantic is dominated by an apparent trend, but this may artificially inflate the anomaly correlations and may not reflect true forecast skill. Over the extended period, the variability becomes more important, such that the detrended ACC of North Atlantic SST is higher than over the shorter period. It is worth noting that for the extended period the reference forecasts such as the persistence are also affected. For the North Atlantic region, the detrended time series show that the ACC of persistence is higher for extended compared to the short period, which is a result of the inclusion of the prolonged multidecadal phases prior to 1960.

We have also demonstrated the possibility to predict the 1920s North Atlantic climate variation and some associated impact on surface climate, including warm European summers and a northward shift of the Atlantic ITCZ. Similar signals were found during the 1990s, consistent with a previous study using a different model [*Robson et al.,* 2013b]. However, model errors limit the prediction of remote impacts, with incorrect SLP patterns leading to incorrect temperatures and precipitation in some regions. Nevertheless, we have shown that extending the hindcast period further back before 1960 is feasible and useful. This may enable other important case studies, such as the prediction historical droughts (e.g., Great Dust Bowl).

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