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Key Points:
- A large ensemble gives high predictability of the subpolar gyre temperature
- The recently observed cooling is forecast to continue
- Impacts are numerous, reduced numbers of tropical storms are clearest

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Forecast cooling of the Atlantic subpolar gyre and associated impacts

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Abstract Decadal variability in the North Atlantic and its subpolar gyre (SPG) has been shown to be predictable in climate models initialized with the concurrent ocean state. Numerous impacts over ocean and land have also been identified. Here we use three versions of the Met Office Decadal Prediction System to provide a multimodel ensemble forecast of the SPG and related impacts. The recent cooling trend in the SPG is predicted to continue in the next 5 years due to a decrease in the SPG heat convergence related to a slowdown of the Atlantic Meridional Overturning Circulation. We present evidence that the ensemble forecast is able to skilfully predict these quantities over recent decades. We also investigate the ability of the forecast to predict impacts on surface temperature, pressure, precipitation, and Atlantic tropical storms and compare the forecast to recent boreal summer climate.

1. Introduction

North Atlantic sea surface temperatures (SSTs) are thought to drive important multiyear weather and climate impacts including temperature and precipitation over land in Europe, America, and Africa [*Knight et al.*, 2006; *Zhang and Delworth*, 2006; *Sutton and Hodson*, 2007; *Sutton and Dong*, 2012], the Atlantic storm track position and/or strength [*Wilson et al.*, 2009; *Woollings et al.*, 2012; *Frankignoul et al.*, 2013], and Atlantic hurricane frequency [*Goldenberg et al.*, 2001; *Smith et al.*, 2010; *Dunstone et al.*, 2011]. The subpolar gyre (SPG, defined here as 60°W–10°W, 50°N–66°N) is a key part of the decadal variability of North Atlantic SSTs, being cool during the 1970s and 1980s and warm since the mid-1990s. This decadal variability is larger than interannual variability [*Knight et al.*, 2005]. Forecasting whether the current warm conditions will continue, decline or even increase over the coming years, along with associated climate impacts, is a key aim of decadal climate predictions.

Diagnostic studies [*Boer*, 2000; 2004; *Branstator et al.*, 2012], idealized experiments with coupled climate models [*Griffies and Bryan*, 1997; *Pohlmann et al.*, 2004; *Hermanson and Sutton*, 2010; *Dunstone et al.*, 2011] and initialized decadal climate predictions [*Pohlmann et al.*, 2009; *Smith et al.*, 2010; *van Oldenborgh et al.*, 2012; *Matei et al.*, 2012; *Chikamoto et al.*, 2012; *Hazeleger et al.*, 2013; *Wouters et al.*, 2013; *Doblas-Reyes et al.*, 2013] all highlight the North Atlantic, especially the SPG, as being potentially predictable on multiyear timescales. This skill is physically underpinned by potential predictability of the Atlantic Meridional Overturning Circulation (AMOC) [*Collins et al.*, 2006; *Pohlmann et al.*, 2013]. Initialization of ocean dynamics was shown to be crucial for predicting the two major changes in the SPG that have occurred since 1960, namely, a cooling during the 1960s and a warming in mid-1990s [*Yeager et al.*, 2012; *Robson et al.*, 2013, 2014b]. Furthermore, some of the resultant climate impacts may have also been predictable in the periods following these changes, including precipitation changes in parts of North and South America, European temperatures, and Atlantic hurricane frequency [*Robson et al.*, 2013, 2014b; *Smith et al.*, 2014; *Müller et al.*, 2014].

Given such robust evidence for skill during historical periods, we investigate actual forecasts of the SPG made using three versions of the Met Office Decadal Prediction System (DePreSys). These show a progressive cooling of the SPG, together with a reduction in the AMOC. Below, we look at the mechanisms and impacts of this cooling and compare the predicted changes to the potential impacts of the subpolar gyre inferred from observations. The ensemble size used here is, to our knowledge, unprecedented in decadal prediction with at least 23 members, enabling robust identification of the mechanisms of SPG changes. These mechanisms are very similar for three different SPG events: the late 1960s, the 1990s, and the present and next few years. We also investigate the predictability of potential impacts of changes in the SPG for Africa, North-East Brazil, the tropical Atlantic, and Europe.

Table 1. Versions of DePreSys Used in This Study, Their Atmosphere and Ocean Resolutions and Ensemble Sizes

System	Atmosphere Resolution	Ocean Resolution	Hindcasts 1960–2007	Forecasts 2008, 2009	Forecasts 2010, 2011	Forecasts 2012
DePreSys_CMIP5	2.5° × 3.75°	1.25° × 1.25°	10	10	20	20
DePreSys_PPE	2.5° × 3.75°	1.25° × 1.25°	9	9	9	9
DePreSys2	1.25° × 1.875°	~1°	4	4	4	10

2. Models and Experiments

We employ three versions of the Met Office Decadal Prediction System (DePreSys; Table 1):

1. DePreSys_CMIP5, based on HadCM3 [*Smith et al*., 2007], as submitted to CMIP5 using anomaly initialization
2. DePreSys_PPE, also based on HadCM3 but using nine variants obtained by perturbing poorly constrained atmospheric and surface parameters in order to sample modeling uncertainty [*Smith et al*., 2010]
3. DePreSys2, based on the latest Hadley Centre climate model, HadGEM3 [*Knight et al*., 2014].

In all versions, initial conditions are generated by relaxing the coupled model to analyses of atmosphere (from ERA40 and ECMWF operational analyses) and ocean [*Smith and Murphy*, 2007], following the anomaly initialization approach [*Smith et al*., 2013].

The skill of the forecasts is assessed by examining retrospective and real-time predictions from 1 November each year since 1960 made with each version of DePreSys. We refer to predictions that can be verified with available observations as “hindcasts,” and those that cannot yet be verified because they extend into the future as “forecasts” (Table 1). We also investigate parallel integrations with each version that are driven by external forcing factors (solar radiation, greenhouse gases, and volcanic and anthropogenic aerosols) identical to those used in DePreSys but are not initialized with the concurrent state of the climate. The difference between DePreSys and these uninitialized simulations (hereafter referred to as uninitialized forecasts) reveals the impact of initialization. For DePreSys_CMIP5 and DePreSys2 external forcings follow the CMIP5 protocol in which future forcing from volcanic eruptions and solar radiation are included in each prediction. For DePreSys_PPE, future changes in volcanic aerosol and solar radiation are projected from the start of each prediction (as in *Smith et al*. [2007, 2010]).

The results shown below are evident in each version of DePreSys. For the variables considered here, the differences in skill between systems are indistinguishable. However, this is not the case for other variables [*Knight et al*., 2014]. We take advantage of the large ensemble size to reduce noise and present results from the grand ensemble. The grand ensemble mean is obtained by averaging the ensemble mean anomalies from the 1960 to 2009 climatology of each version (thus, each version is given equal weight). A 90% probability range for verification with observations is calculated by using Student’s *t* distribution together with the average of the three variances. We investigate the role of ocean dynamics and its predictability by assessing predictions against the ocean analysis used for initialization for temperature or density and against the average of the three assimilation integrations for heat convergence. We note that despite the lack of ocean observations over the historical period, the SPG was actually relatively well observed such that the major changes are robust across different data sets [*Robson et al*., 2012a]. Furthermore, the AMOC in the three assimilation runs are similar (pairwise correlations are 0.7 or higher) and compare reasonably well with RAPID observations [*Hermanson et al*., 2014]. The model surface temperature, mean sea level pressure, and precipitation are verified by comparison with HadCRUT3 [*Brohan et al*., 2006], HadSLP2 [*Allan and Ansell*, 2006], and GPCC [*Schneider et al*., 2011], respectively.

3. Forecast of the SPG

The observed 5 year mean temperature averaged over the upper 500 m of the SPG is shown in Figure 1a (red and blue shading). There is a marked cooling in the late 1960s followed by a period with below average temperatures, and a warming in the 1990s followed by a period with above average temperatures. The SPG has been cooling slightly since the mid-2000s, but remains well above average. The grand ensemble 5 year hindcasts that were intialized between 1960 and 2007 (diamonds) show high skill in predicting the decadal variability of the observations (Pearson’s correlation $r = 0.87$, $p << 0.001$ with the effects of autocorrelation

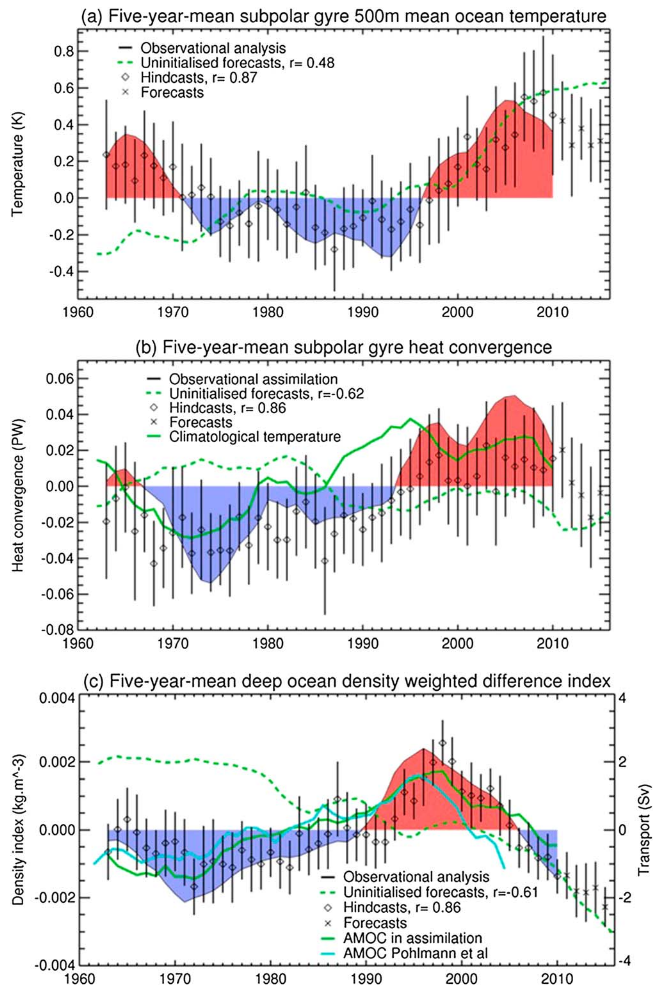

Figure 1. Hindcasts, uninitialized forecasts, forecasts and observational analyses or assimilations for 5 year mean (years 1–5) anomalies of (a) SPG temperature averaged over the upper 500 m, (b) ocean heat transport convergence into the SPG, and (c) deep Atlantic density index (see text). The year indicates the central year in the 5 year mean. Also shown in Figure 1c is the AMOC at 45°N from *Pohlmann et al.* [2013], scaled to have the same standard deviation as the AMOC in the assimilation. Red/blue shading is the same as the black line. The 90% probability spread of the hindcasts/forecasts is indicated by the vertical lines. Figure 1a uses additional trend correction following *Kharin et al.* [2012].

taken into account) consistent with previous studies [*Robson et al.*, 2012b, 2014b]. The forecasts that were initialized between 2008 and 2012 (crosses) all show a general trend for further decreases in temperature, continuing the observed trend. The 2012 forecast spread suggests that the chance of the observed warm SPG mean temperature anomaly of 2003–2007 (0.53) occurring again in 2013–2017 is less than 6%.

To gain further confidence in this forecast we examine the physical mechanisms that control SPG temperatures. Previous studies showed that the 1990s SPG warming was driven by increased convergence of ocean heat transport resulting from an increase in the AMOC [*Robson et al.*, 2012b; *Yeager et al.*, 2012], and the 1960s cooling was driven by reduced ocean heat transport convergence following a reduced AMOC [*Robson et al.*, 2014b]. The hindcasts show changes in ocean heat transport convergence, consistent with these earlier events. We find that changes in ocean heat transport convergence are skilfully predicted by the hindcasts (Figure 1b, diamonds; $r = 0.86$, $p << 0.001$, assessed against the convergence in the assimilation). The forecasts show a continued decrease in ocean heat transport convergence, consistent with a cooling SPG.

We further investigate the role of ocean dynamics in driving changes in ocean heat transport convergence by computing the grand ensemble assimilation heat transport convergence using climatological temperatures (from each assimilation averaged over 1960–2009) but time varying velocities (Figure 1b, solid green line). This captures the decrease in the 1960s, the increase from the 1970s to the 1990s, and the recent decrease (last few years), suggesting that changes in ocean velocities rather than temperatures have been the most important drivers of ocean heat convergence, and hence SPG temperature, in agreement with previous studies [*Robson et al.*, 2012b, 2014b; *Yeager et al.*, 2012].

Changes in meridional ocean velocities in the SPG region are largely driven by changes in the west-east density gradient at around 1200–3000 m depth [*Hodson and Sutton*, 2012; *Roberts et al.*, 2013], which impacts on the AMOC return flow. As observations of the AMOC are rare at these latitudes, we consider recent trends in density at these depths (Figure 2, top), which can be estimated from fewer observations [*Smith and Murphy*, 2007] and noting that the SPG region was relatively well observed historically [*Abraham et al.*, 2013]. There has been a clear reduction in density along the western boundary, especially in the Labrador Sea, consistent with a weakening of the west-east density gradient and a reduction of the AMOC return flow. We construct an index of the difference in density (west minus east) between two boxes (see blue boxes in

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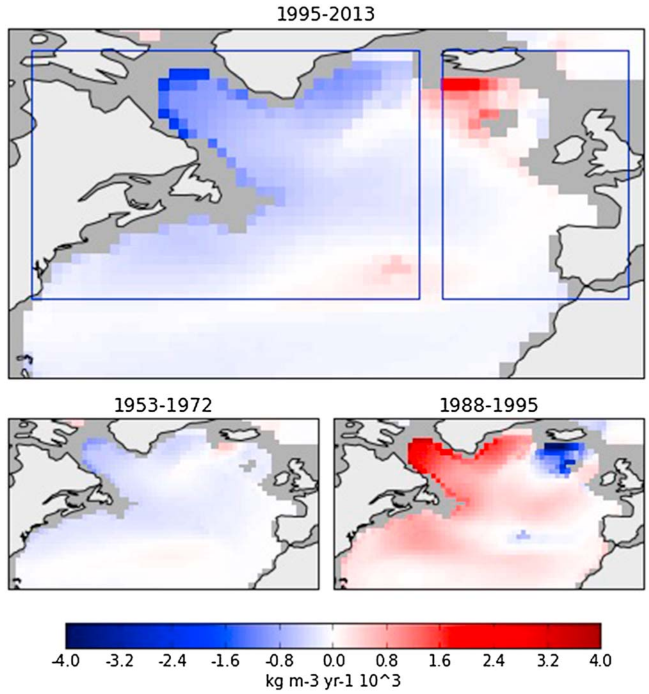

Figure 2. Density trend in the 1200–3000 m layer for (top) 1995–2013 and for two earlier periods (bottom left) 1953–1972 (cooling period) and (bottom right) 1988–1995 (warming period). Computed from the Met Office ocean analysis [*Smith and Murphy*, 2007].

Figure 2, top) weighted by their respective volumes. Decadal variations of this index (Figure 1c) agree well with the AMOC at 45°N in the assimilations (green line, right hand axis) and an estimate of the AMOC at 45°N from 10 recent ocean syntheses (cyan line, *Pohlmann et al*., 2013). This index is also skilfully predicted by the hindcasts ($r = 0.86$, $p << 0.001$) and is forecast to decrease further out to 2017. Using the index to choose years that also show decadal trend, we investigate the deep density trend patterns during the 1960s SPG cooling and the 1990s SPG warming (Figures 2, bottom left and 2, bottom right). Remarkably similar patterns are found, implying that similar dynamical processes appear to have been dominant in these earlier periods of change.

Note that the uninitialized forecasts (dashed green lines in Figure 1) fail to capture the observed recent cooling. While they do simulate a warming of the SPG between 1970 and 2005 in agreement with observations, this is likely for different reasons than in the initialized hindcasts since changes in ocean heat transport convergence and density index are opposite to those observed (this was also found by *Yeager et al*. [2012]). Furthermore, uninitialized forecasts fail to simulate the warm conditions before 1970. This highlights the need for initialized predictions. However, further work is needed to understand the role of external forcing, perhaps through indirect aerosol effects [*Booth et al*., 2012; *Dunstone et al*., 2013], which are not included in these models or natural forcing (such as solar and volcanic: [*Menary and Scaife*, 2014]).

In summary, changes in SPG temperature since the 1960s were likely driven by changes in ocean heat transport convergence as a result of changes in the AMOC. Initialized predictions using DePreSys capture both the SPG cooling during the 1960s and the warming during the 1990s along with changes in ocean dynamics. Recent observations suggest that the AMOC may already be declining [*Smeed et al*., 2013; *Robson et al*., 2014a], and our forecasts show a continued cooling of the SPG out to 2017 driven by reduced ocean heat transport convergence resulting from a continued reduction in the AMOC. Since past changes in SPG temperature are thought to have driven important climate impacts, we also examine the predicted climate impacts.

4. Inferred Climate Impacts

Figure 3 shows the amplitude of variability associated with SPG changes (in SST) diagnosed from composite differences in (June, July, and August) between warm and cold SPG decades for surface temperature, mean sea level pressure, and precipitation. It shows that a warm SPG is associated with a warm northern Tropical Atlantic, warm mainland US, and warm European temperatures, especially in the eastern Mediterranean. These regions also experience lower surface pressure on average. There is also a low pressure over western Europe, which is colocated with a signal for wet summers. The rainfall pattern in the tropical regions around the Atlantic indicates a northward shift of the Intertropical Convergence Zone (ITCZ), consistent with increased hurricane numbers. A simple forecast of impacts would be that these features of the climate, which have been observed in recent years, will become less likely to occur.

To investigate potential climate impacts simulated by the model, we take a similar approach to *Robson et al*. [2013, 2014b] and compute multiyear differences between forecasts and recent hindcasts. This highlights

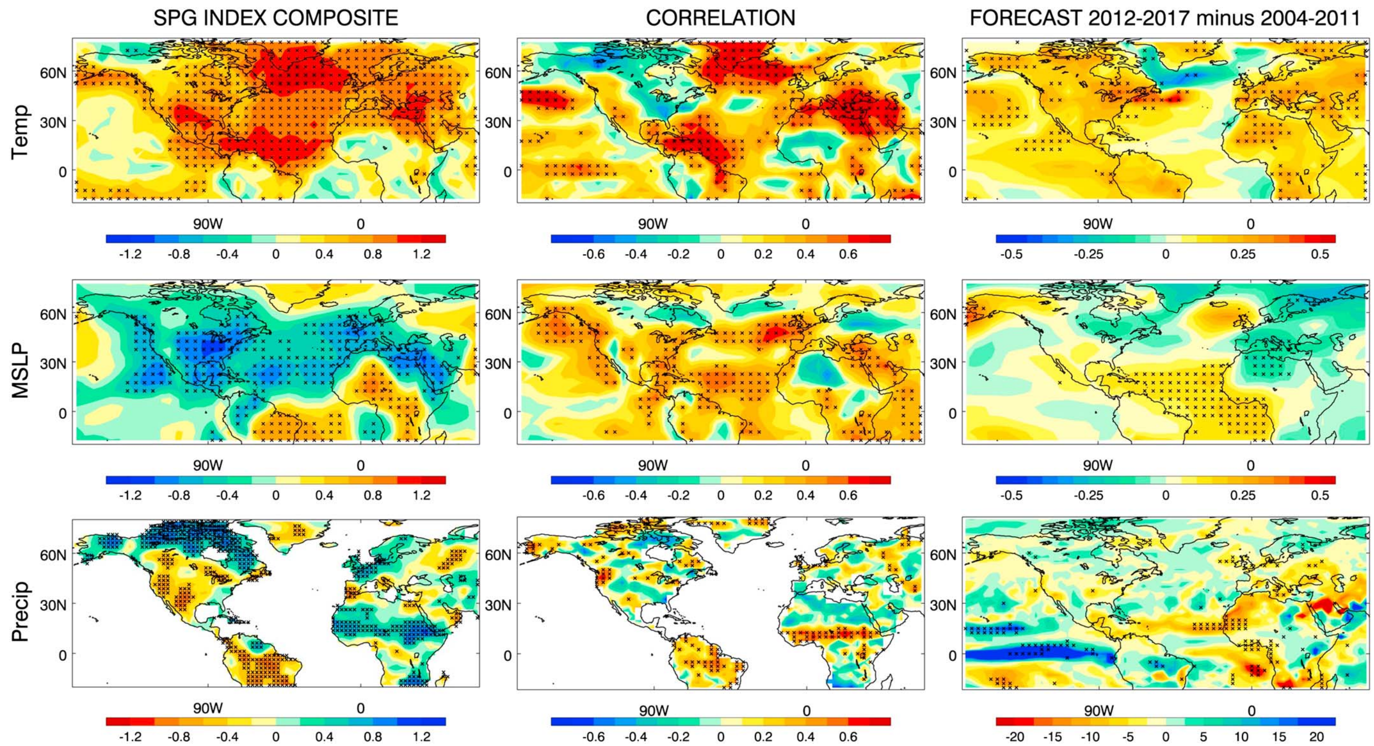

Figure 3. (left column) A composite of potential SPG impacts inferred from observations, (middle column) correlation skill for the grand ensemble of model hindcasts and (right column) the forecast all for boreal summer (June–August) for 1.5 m temperature, mean sea level pressure, and precipitation (rows). Figure 3 (left column) shows half the observed composite difference between warm (1930–1940, 1954–1956, 1999–2005) and cold (1921–1923, 1969–1976, 1982, 1985–1992) SPG decades, following *Smith et al*. [2012]. Units are standard deviations of 9 year rolling window smoothed fields. Figure 3 (middle column) shows the correlation skill for predicting the coming 6 year mean relative to the previous 8 years (following similar quantities investigated by *Robson et al*. [2013, 2014b]; see text for further explanation). Figure 3 (right column) shows the forecast for 2012–2017 relative to the previous 8 years. From top to bottom, units are K, hPa, and % change from climatology. Crosses mark grid boxes where anomalies are significant at the 95% level. See the Appendix A for more details on the method.

potentially important changes from recent conditions that might be masked by trends if a longer climatological period were used. This approach also effectively removes biases and noise is reduced by combining several hindcasts together. Furthermore, the influence of trends on correlation skill is reduced, thereby avoiding high correlations that can arise from the trend. We use 5 years from each of two consecutive hindcasts (making a 6 year mean, four of which overlap plus one independent year from each hindcast) relative to the four most recent hindcasts prior to them (making an 8 year mean). For example, the two hindcasts intialized in November 1968 and 1969 make a mean including the summers 1969–1974 and are compared to a climatology created from the hindcasts initialized in November 1960–1963, which includes the summers 1961–1968. To quantify skill, these quantities are compared to the difference between the same years in observations. The correlation skill of the grand ensemble for predicting surface temperature, pressure, and rainfall is shown in Figure 3 (middle column).

Figure 3 (right column) shows the grand ensemble forecast using the same approach as the hindcasts. These are the two 5 year forecasts initialized in 2011 and 2012 for the period 2012–2017, relative to hindcasts that started in 2003–2006 for the years 2004–2011. This forecast consists of an ensemble of 76 members, showing future changes relative to recent (forecast) conditions.

One of the clearest signals in this forecast is for higher pressure and decreased rainfall in the northern Tropical Atlantic Ocean. This is consistent with the observed composites (Figure 3, left column) and in a region where there is some correlation skill (Figure 3, middle column). Previous studies suggest a link between SPG temperatures and the frequency of Atlantic tropical storms [*Goldenberg et al*., 2001; *Smith et al*., 2010, 2014; *Dunstone et al*., 2011]. We therefore also investigate predictions of Atlantic tropical storms. Figure 4 shows the 5 year mean HURDAT2 observations of tropical storms [*Landsea and Franklin*, 2013] since 1960 along with the hindcasts and forecasts of storm counts from the grand ensemble. The hindcasts appear

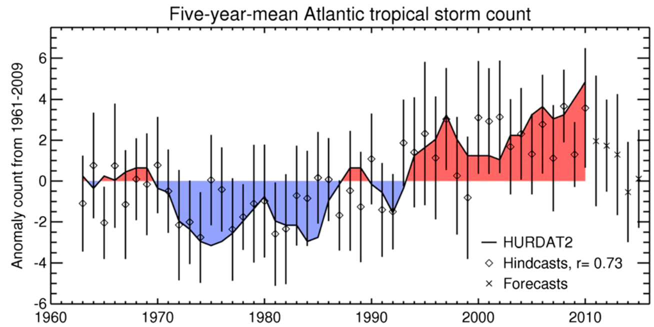

Figure 4. Tropical storm counts for storms in the latitude band 5°N–25°N in the Atlantic that last more than 2 days. The year indicates the central year of the 5 year mean. Following *Smith et al.* [2010], model storms are tracked in daily field of sea level pressure and standardized to have the same mean and variance as the observations. The 50% probability spread of the hindcasts/forecasts is indicated by the vertical lines.

to be skilful and the recent forecasts for tropical storm counts show an overall downward trend in the coming years, consistent with expected impacts from a cooling SPG.

Other expected impacts of a cooling SPG are not clear in the forecast. For example, warmer summers are predicted in the Mediterranean, which is contrary to our expectation for a cooling of the SPG. The ITCZ does not show a clear shift in the forecast, although there are some indications of reduced rainfall in the western Sahel and increased rainfall in North-East Brazil. The probability of wet summers in western Europe is expected to decrease as the SPG cools [*Dong et al*., 2013]. The precipitation forecast also shows a small region with significantly lower precipitation over the British Isles and Ireland. However, the ensemble shows no skill in predicting rainfall for this region and although the pressure forecast map shows coincident high pressure, it is in a region with large variability and is not significant.

5. Discussion and Conclusions

We have investigated the decadal predictability of the North Atlantic subpolar gyre (SPG) and associated physical mechanisms and climate impacts using three versions of the Met Office Decadal Prediction System (DePreSys) resulting in a uncommonly large ensemble. Upper 500 m temperature in the SPG was found to be highly predictable and driven by predictable changes in ocean heat transport convergence related to changes in the Atlantic Meridional Overturning Circulation (AMOC) in our models.

Recent observations show a slight cooling of the SPG. We present forecasts from DePreSys predicting a continued decrease in SPG temperature, driven by a weakening AMOC leading to decreased heat transport convergence into the SPG. The AMOC is expected to decrease with climate change [*Meehl et al*., 2007], leading to relative cooling in the SPG. However, the SPG cools in the forecasts but does not in uninitialized forecasts. This suggests that ocean dynamics not captured in our uninitialized forecasts may have a significant influence on the evolution of the North Atlantic over the coming years. The forecast signals presented here therefore arise from a combination of climate change and internal variability and/or forced changes not captured by our models (but introduced through initialization) and show the benefits of initialization in decadal climate predictions.

Observations and previous studies suggest that the recent warm SPG has increased the likelihood of several climate impacts including increased hurricane numbers, wet European summers, increased Sahel rainfall, reduced summer rainfall over the Amazon and south-west USA, and warm summer temperatures over much of the USA and Europe. Our forecast is for a cooling of the SPG but not a complete reversal to cold conditions. As such, we expect climate impacts related to a warm SPG to persist but become less likely. Indeed, our forecast does indicate a reduction in Atlantic tropical storms, consistent with higher pressure and lower rainfall in the northern tropical Atlantic. There is also a decrease in summer rainfall in western Europe with a coincident high-pressure signal but the signals are weak, and the historical skill of the forecast system is too low to provide confidence in these signals. The predicted cooling of the SPG highlighted is potentially a significant event, and further studies with other models are encouraged to provide more confidence in associated climate impacts.

Appendix A: Statistical Significance in Figure 3

The stippling with crosses in Figure 3 shows anomalies as significant when the null hypothesis that they are zero can be rejected with $p < 0.05$. For the composites, assuming 4 degrees of freedom, the contour values of

±0.5 and larger magnitude are statistically significant [*Smith et al*., 2012]. For the correlations, autocorrelation is used to reduce the degrees of freedom before the significance is calculated. In the forecast, the six individual years of the forecast are compared to the 8 years in the hindcast with a two-sided *t* test to determine significant anomalies.

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