Multi-year predictability of the tropical Atlantic atmosphere driven by the high latitude North Atlantic Ocean

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[1] Using idealised model experiments we show that the tropical Atlantic main hurricane development region (MDR) is potentially one of the most predictable regions for atmospheric variables such as precipitation and wind shear on multi-year timescales. Similarly we also find predictability for the number of tropical storms and the position of the inter-tropical convergence zone. Further experiments that withhold data in different parts of the ocean identify the North Atlantic sub-polar gyre as the key region for driving the skill in the model MDR. This further highlights the importance of observing the high-latitude North Atlantic Ocean for initialising future decadal predictions. **Citation:** Dunstone, N. J., D. M. Smith, and R. Eade (2011), Multi-year predictability of the tropical Atlantic atmosphere driven by the high latitude North Atlantic Ocean, *Geophys. Res. Lett.*, *38*, L14701, doi:10.1029/2011GL047949.

1. Introduction

[2] There is growing interest in the possibility that initialised climate models may be able to provide skilful predictions on inter-annual to decadal timescales [*Smith et al.*, 2007; *Keenlyside et al.*, 2008; *Pohlmann et al.*, 2009; *Mochizuki et al.*, 2010]. Assessing skill in reality is difficult because the historical period over which tests can be conducted provides only a limited sample, and is further complicated by the background global warming trend and unpredictable natural forcings such as volcanic eruptions. Idealised model studies that attempt to predict the evolution of a coupled climate model [*Griffies and Bryan*, 1997; *Collins*, 2002; *Pohlmann et al.*, 2004; *Dunstone and Smith*, 2010; *Msadek et al.*, 2010] therefore provide valuable additional information, both to increase confidence in real predictions and to investigate the sources of any skill.

[3] Previous idealised model studies show that the Atlantic meridional overturning circulation (MOC) is potentially predictable on interannual to decadal timescales [*Griffies and Bryan*, 1997; *Collins and Sinha*, 2003; *Pohlmann et al.*, 2004; *Dunstone and Smith*, 2010; *Msadek et al.*, 2010]. The MOC is believed to drive low frequency changes in sea surface temperature (SST) in the North Atlantic [*Knight et al.*, 2005], which have in turn been linked to regional climate variability including European and North American summer climate, rainfall in north east Brazil and the African Sahel, and Atlantic hurricanes [*Sutton and Hodson*, 2005; *Knight et al.*, 2006; *Zhang and Delwoth*, 2006]. However to date there is little evidence from idealised studies for skill in the tropical atmosphere on multi-annual timescales.

[4] In a recent study, *Smith et al.* [2010] reported skilful multi-year predictions of Atlantic hurricane frequency. Using experiments with and without the initialisation of observations they found that skill came from both external forcings and additionally from initialisation. Improvements from initialisation were consistent with atmospheric teleconnections linking wind shear and precipitation in the tropical Atlantic to SST in the North Atlantic sub-polar gyre and tropical Pacific. Here we follow up these results by using idealised model experiments to further investigate the internal predictability in the tropical Atlantic atmosphere and to determine the relative importance of different regions in driving this predictability.

2. Experimental Set-up

[5] Our experiments are based around a long control run of the HadCM3 coupled climate model. The control run has no inter-annually varying external forcings and is in excess of 5000 years long. We examine predictability in a set of 26 forecasts with start dates from the last 3000 years. The start dates are selected at random but are separated from each other by more than 50 years in order to ensure independence of initial conditions. Each forecast is 10 years long and consists of five ensemble members. All forecasts commence on the first day of December. We focus on the hurricane main development region (MDR) [*Goldenberg et al.*, 2001] during the hurricane season (June to November, JJASON). Hence the forecast of the first JJASON period has a lead time of six months.

[6] We assess predictability by comparing two five member ensembles of model integrations: 'Perfect' and 'Assim'. The 'Perfect' ensemble is generated by applying almost bit-level (5×10^{-7} K) random perturbations to each SST field grid-point in the model initial conditions for a given start date. Except for the small SST perturbation each ensemble member has full and instantaneous knowledge of all model variables in the ocean and atmosphere (including currents and winds).

[7] The 'Assim' ensemble is initialised by assimilating monthly average full-depth temperature and salinity (T & S) ocean data for one year before each forecast start date. The monthly data are taken from the original control run and assimilated at all ocean model locations. We follow the method of the UK Met Office Decadal Prediction System (DePreSys) [*Smith et al.*, 2007] and use a simple nudging technique with a strong (6 hour) relaxation constant. Linear interpolation is used between monthly values to obtain the increment at each model timestep. Similarly we assimilate monthly average fields of ice thickness and concentration

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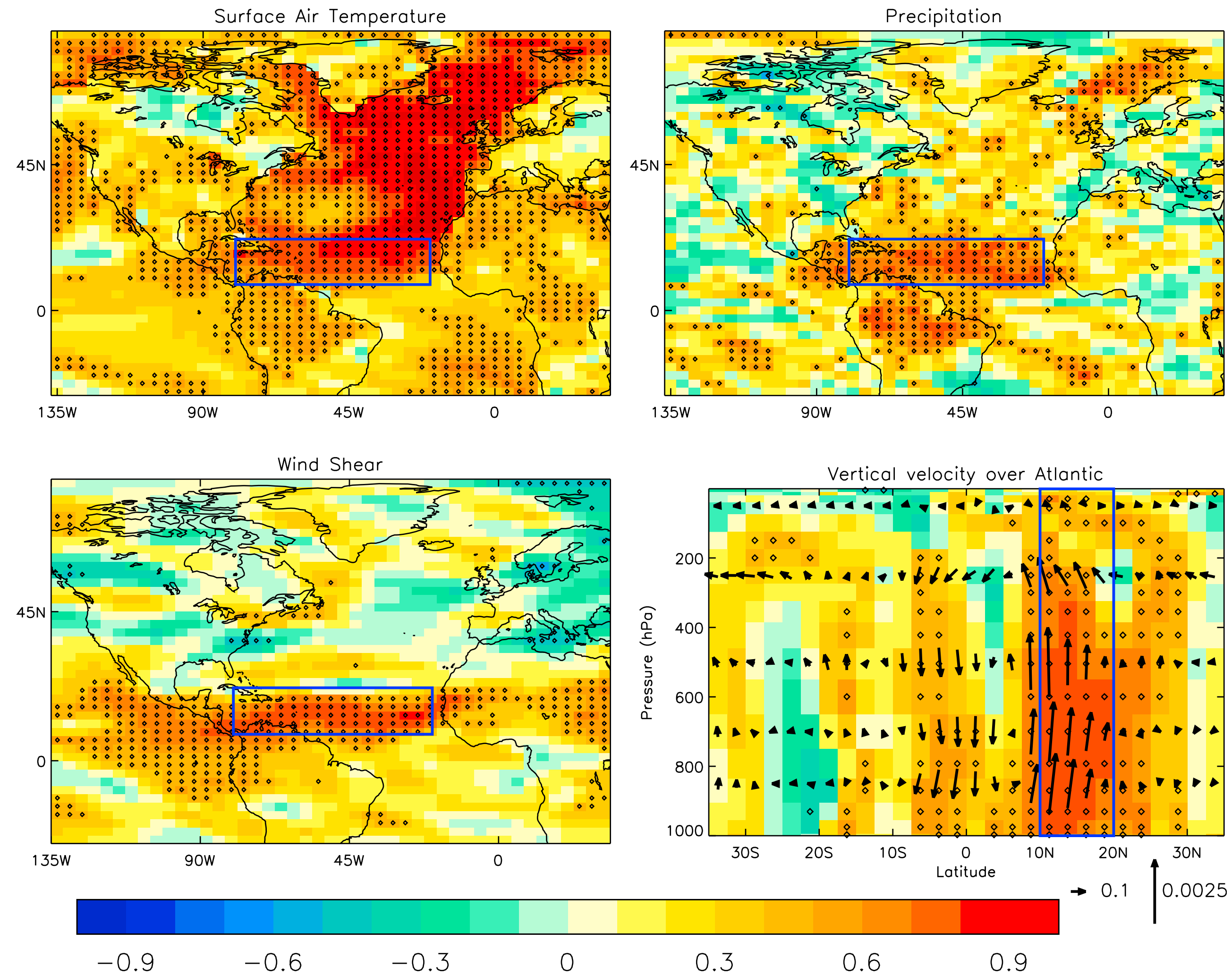

Figure 1. Anomaly correlations for JJASON of the second five year (Years 2 to 6) ensemble means of the Perfect and the Assim forecast experiments. SAT, precipitation, wind shear and vertical velocity (along with wind vectors from a composite analysis, see text for details) are shown. The blue box shows the location of the main hurricane development region (MDR). Stippled regions have correlations that are statistically significant at the 5% level (see text).

into the model. Five member ensembles are created using the same random perturbation as described for the Perfect set of experiments.

[8] We assess how well the Assim ensemble mean is able to predict the Perfect ensemble mean. Using the Perfect ensemble mean, rather than an individual ensemble member, as the truth focuses on the most predictable signals, because less predictable components will have very different realisations in the individual ensemble members, and so will contribute less to the ensemble mean. This increases the statistical significance of the most predictable signals, and is especially important for investigating the sources of skill (Section 4). However, it is unrealistic in the sense that there is only a single realisation of the real world, and we stress that the absolute levels of skill in our analyses do not necessarily provide any guidance on the absolute skill that could be achieved in reality. In fact this is true for all idealised predictability studies, even when skill is assessed against a single ensemble member, because the predictability of the atmosphere depends critically on the model's ability to simulate ocean atmosphere coupling correctly. Instead, our analysis indicates the relative predictability of different regions in our model, and provides a framework for diagnosing the sources of skill (Section 4). However, to illustrate that unpredictable future events (e.g., ENSO activity) do not dominate the skill we show equivalent skill maps assessed against a single member in the auxiliary material.[1]

3. Predictability in the Tropical Atlantic

[9] Correlation maps for four atmospheric variables of interest are shown in Figure 1, where the value at each gridpoint represents the correlation of the two experiments ensemble means over the 26 start dates. These maps are for the JJASON seasons in the second five year mean period (Years 2–6) and so correspond to a forecast lead time of 18 months. Similar results are obtained for all five year periods out to four years (not shown). Statistical significance (at the 5% level) is assessed using a 1-sided student t-test.

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047949.

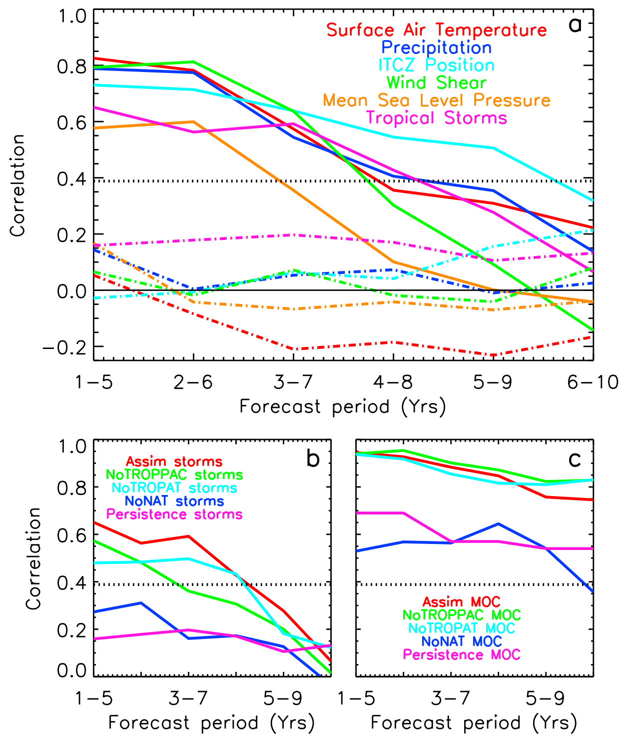

Figure 2. Correlation skill as a function of lead time for five year means of different climate variables. (a) Area-averaged in the MDR region. Dot-dash lines show the skill of persistence. (b, c) Skill in tropical storms and the MOC at 26 N for the Assim and data withholding experiments. Correlations above the horizontal dashed line are significant at the 5% level.

[10] As expected, in Figure 1 surface air temperature (SAT) predictions are relatively skilful in the sub-polar gyre (SPG) region of the North Atlantic. However, there is also relatively high skill throughout most of the North Atlantic including the MDR region. Importantly, we also find significant skill in other atmospheric variables in the MDR, including precipitation, wind shear (U250 hPa - U850 hPa) and zonally integrated vertical velocity over the Atlantic basin. Indeed, these variables are considerably more predictable in the MDR than in other regions.

[11] Figure 2a shows the skill in the MDR as a function of forecast lead time. For this we first calculated the area-average of each variable in the MDR region, for each ensemble member, before calculating the correlations between ensemble means. Most variables show statistically significant skill up to the year 4 to 8 forecast period. In contrast, persisting the five year anomaly immediately prior to each start date shows no significant skill for any variable (dashed lines). We also assessed the latitudinal position of the ITCZ, diagnosed by fitting a Gaussian profile through the grid-points from the zonal average precipitation in the tropical Atlantic basin. Interestingly, the position of the ITCZ is predicted with similar skill to precipitation in the MDR, suggesting that changes in the tropical Atlantic atmosphere in our model are associated with shifts in the position of the ITCZ.

[12] Having found relatively high predictability in the MDR SAT and wind shear, variables known to be important for controlling tropical storm development, we also investigate predictions of the numbers of tropical storms occurring in each five year period. We count storms using a simple algorithm that tracks daily minima in the MSLP field as used by *Smith et al.* [2010]. Although the coarse resolution of HadCM3 does not enable a realistic simulation of the intensity of tropical storms, the annual variability in the observed numbers of tropical storms is well reproduced in seasonal forecasts. We therefore have confidence that by assessing the skill in predicting model storms we are probing some of the relevant physical mechanisms. As shown by the purple line in Figure 2a, we find significant skill in the numbers of storms.

4. Origins of MDR Predictability

[13] In order to gain further insight into the mechanisms behind the predictability of the MDR we assess the relative importance of different regions by performing three additional experiments. Each experiment removes the ocean assimilation in a selected region and instead relaxes the model to a climatological state (calculated from the 50 years immediately preceding each of the 26 start dates). The three regions are shown in Figure 3: No Tropical Pacific (NoTROPPAC), No North Atlantic (NoNAT) and No Tropical Atlantic (NoTROPAT). The eastern tropical Pacific and the North Atlantic sub-polar gyre regions both contributed to the skill of Atlantic tropical storms in the study by *Smith et al.* [2010]. The tropical Atlantic itself (containing the MDR) would be an obvious choice to initialise if persistence of local SST anomalies are responsible for multi-annual predictability or if other modes of decadal variability may exist in the Tropical Atlantic and be predictable [e.g., *Kossin and Vimont*, 2007]. Except for withholding data the experiments are identical in setup to those described in Section 2. Relaxing the region to climatology during the assimilation year ensures that signals are unable to propagate from other regions thereby isolating the region of interest. In order to minimise potential problems at the boundary between regions of ocean assimilation and regions of relaxation to climatology, we smoothly transition between the two over a latitudinal band of width 10° (as illustrated in Figure 3).

[14] Skill maps for SAT, precipitation, wind shear and vertical velocity are shown in Figure 3. Given that all experiments have removed information the correlations are lower than those achieved by the original Assim experiment, as expected. However, we are primarily interested in the relative skill of these experiments. From Figure 3 it is clear that the NoNAT experiment has the greatest impact on the skill in the MDR, while the NoTROPPAC and NoTROPAT experiments show very similar, and significant, correlations. This is also true for tropical storm predictions (Figure 2b).

5. Discussion and Conclusions

[15] We present robust evidence from idealised climate model experiments that the tropical Atlantic atmosphere is a region with relatively high potential predictability on multi-annual timescales in HadCM3. Furthermore, by withholding ocean data in different regions we identify the North Atlantic SPG region as a key driver of this skill. If the SPG region is not initialised then skill in predicting the tropical Atlantic atmosphere, including tropical storm numbers, is

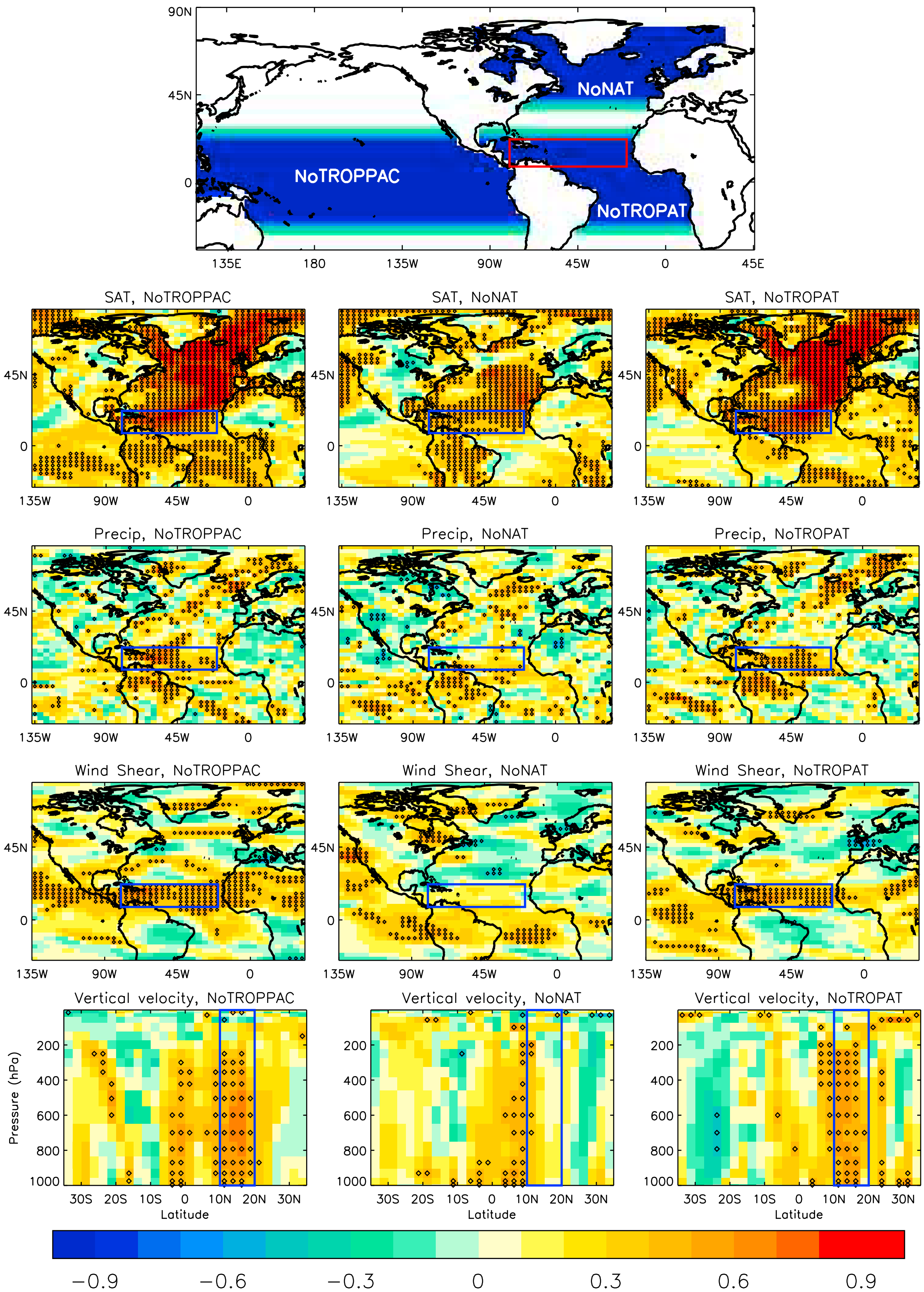

Figure 3. (top) Diagram illustrating the locations of the three ocean regions where the model is relaxed to climatology. The interface regions where we smoothly ramp down the strength of assimilation are shown in green, along with the location of the MDR in red. (bottom) As Figure 1 but for each of the data withholding experiments.

significantly decreased. Conversely, removing either the tropical Pacific or Atlantic has relatively little impact.

[16] For an ocean region to force a future predictable change in the atmosphere it must itself be predictable on the required timescale. In the first forecast year, the tropical Pacific does have a significant impact on skill in the tropical Atlantic. We interpret this as a consequence of skillful predictions of ENSO. However, for five year mean periods beyond the first year, the predictability in the tropical Pacific decreases rapidly and the influence of the North Atlantic dominates in HadCM3.

[17] Key questions are: what drives the variability in SPG temperature and how does the SPG influence the tropical Atlantic atmosphere? Previous work [e.g., *Knight et al.*, 2005; *Delworth and Mann*, 2000] has linked low frequency changes in SPG temperature to variations in the strength of the Atlantic meridional overturning circulation (AMOC). Consistent with this we find relatively high skill in predicting the AMOC at 26°N (Figure 2c) for all experiments except NoNAT. This suggests that density anomalies in the SPG region influence the AMOC at 26°N. However, we cannot determine whether the AMOC plays an active role in our experiments, and leave this for future work.

[18] We investigate the mechanism through which the SPG influences the tropical Atlantic by producing a composite of the difference in atmospheric circulation between the eight warmest and the eight coolest sub-polar gyre SST periods for years 2 to 6 of the 26 start dates from the Perfect ensemble (Figure 1, bottom right, arrows). This shows an anomalous Hadley circulation with anomalous uplift in the MDR region, consistent with *Smith et al.* [2010], *Kang et al.* [2009] and the response to North Atlantic freshwater hosing experiments [e.g., *Zhang and Delworth*, 2005]. This acts to weaken the Hadley circulation and transport less heat northward and could be explained in terms of the atmospheric energy budget [*Kang et al.*, 2009)] a warm SPG warms the northern hemisphere more than the southern, and the atmospheric circulation responds to redistribute the heat via the upper branch of the anomalous Hadley cell. The rising branch of this anomalous Hadley cell coincides with the MDR (Figure 1, bottom right), and would be expected to influence tropical storm formation by modifying atmospheric ascent, precipitation and wind shear. Vertical velocity in the MDR is relatively highly predictable (Figure 1, bottom right, colour contours), but the skill is greatly reduced when initial conditions in the SPG are withheld (Figure 3), consistent with the impact on other variables including storms (Figures 2 and 3).

[19] Previous studies using atmosphere only models that prescribe SST anomalies in the extra-tropics [e.g., *Vitart and Anderson*, 2001; *Lu and Delworth*, 2005; *Sutton and Hodson*, 2005] report little or no impact on the tropical atmosphere. In contrast, our results show a relatively large impact of the extra-tropics in forcing the tropical atmosphere which is in better agreement with coupled ocean-atmosphere studies [e.g., *Liu and Yang*, 2003]. To reconcile these results it is likely that the extra-tropics force the tropical atmosphere by changing the tropical SST. Future studies of this mechanism therefore require a coupled model framework.

[20] Our study highlights the potential importance of the SPG region for inter-annual to decadal climate prediction, suggesting that future ocean observing systems should ensure this region has good coverage. However, our results use a single model, and further studies are required to establish if the MDR predictability, and relationship with the North Atlantic SPG, are robust across other climate models. Indeed, *Hawkins et al.* [2011] obtained skilful statistical predictions of multi-annual MDR surface temperature arising largely from the SPG region, although the results were model dependent. It is also important to note that external anthropogenic and natural climate forcings, absent from our experiments, may also contribute to the variability in the MDR. Furthermore, in common with all predictability studies, our model experiments do not provide a quantitative assessment of the skill achievable in the real world. Nevertheless, in our idealised experiments we have shown that the extratropical Atlantic ocean can drive the tropical atmosphere and generate predictable low-frequency internal variability in the tropical atmosphere. This is encouraging for the extension of initialised forecasts beyond the seasonal timescale.

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