The Role of the Atlantic Ocean in Climate Forecasting

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ABSTRACT

We discuss evidence from observations and atmosphere model studies concerning the influence of Atlantic Ocean conditions on winter climate in the North Atlantic / European region. Both sources of evidence suggest the Atlantic influence is significant, and that the atmospheric response to Atlantic variability projects on the North Atlantic Oscillation pattern. It is suggested that the mechanism involves the impact on local convection of SST anomalies in the tropical Atlantic region, and the consequent excitation of a Rossby wave response that propagates into midlatitudes. There is now an important need to investigate the relevance of these results to coupled model based seasonal and longer term climate forecasts.

1 Introduction

In the development of systems for seasonal forecasting attention has focused overwhelmingly on the tropical Pacific ocean. This focus is justified by the pre-eminent importance of ENSO as a cause of interannual variability in climate on a global scale. However, the oceanic influence on climate variability is not limited to ENSO or to the tropical Pacific. Those with a particular interest in the climate of Europe might reasonably expect that attention should be paid to the Atlantic Ocean. In this paper we discuss evidence that the Atlantic exerts a significant influence on climate variability. We review some evidence from observations and then present recent results from experiments with an atmospheric General Circulation Model. The discussion focuses primarily on the climate of the North Atlantic / European region, and on boreal winter.

2 Observational Evidence for an Atlantic Ocean Influence on Climate

A natural starting point in the search for evidence of an oceanic influence on climate variability is to consider correlations (or covariances) between ocean and atmosphere fields. Simultaneous correlations, however, tend to be dominated, particularly in the extratropics, by the ocean's response to atmospheric variability. Hence it is necessary to consider lead/lag correlations, in which the ocean fields lead the atmosphere fields. Czaja and Frankignoul (2002) performed a lagged maximum covariance analysis (MCA) between Atlantic ocean sea surface temperatures (SST; 20S-70N) and Atlantic sector 500hPa geopotential height (GPH). Their results indicate a significant influence of Atlantic Ocean conditions on the circulation of the atmosphere over the North Atlantic region in early winter (Nov-Dec-Jan). Figure 1, taken from their study, shows the leading MCA mode between summertime SST and early winter GPH. The SST pattern has a horseshoe shape, while the GPH field shows a dipole structure that is similar to the pattern of the North Atlantic Oscillation (NAO; Hurrell, 1995). The sign of the association is that positive SST anomalies in the low latitude North Atlantic are associated with a negative NAO index (according to the usual NAO sign convention). The timeseries is dominated by multi-annual variability (but note that the lowest frequencies were removed from the analysis).

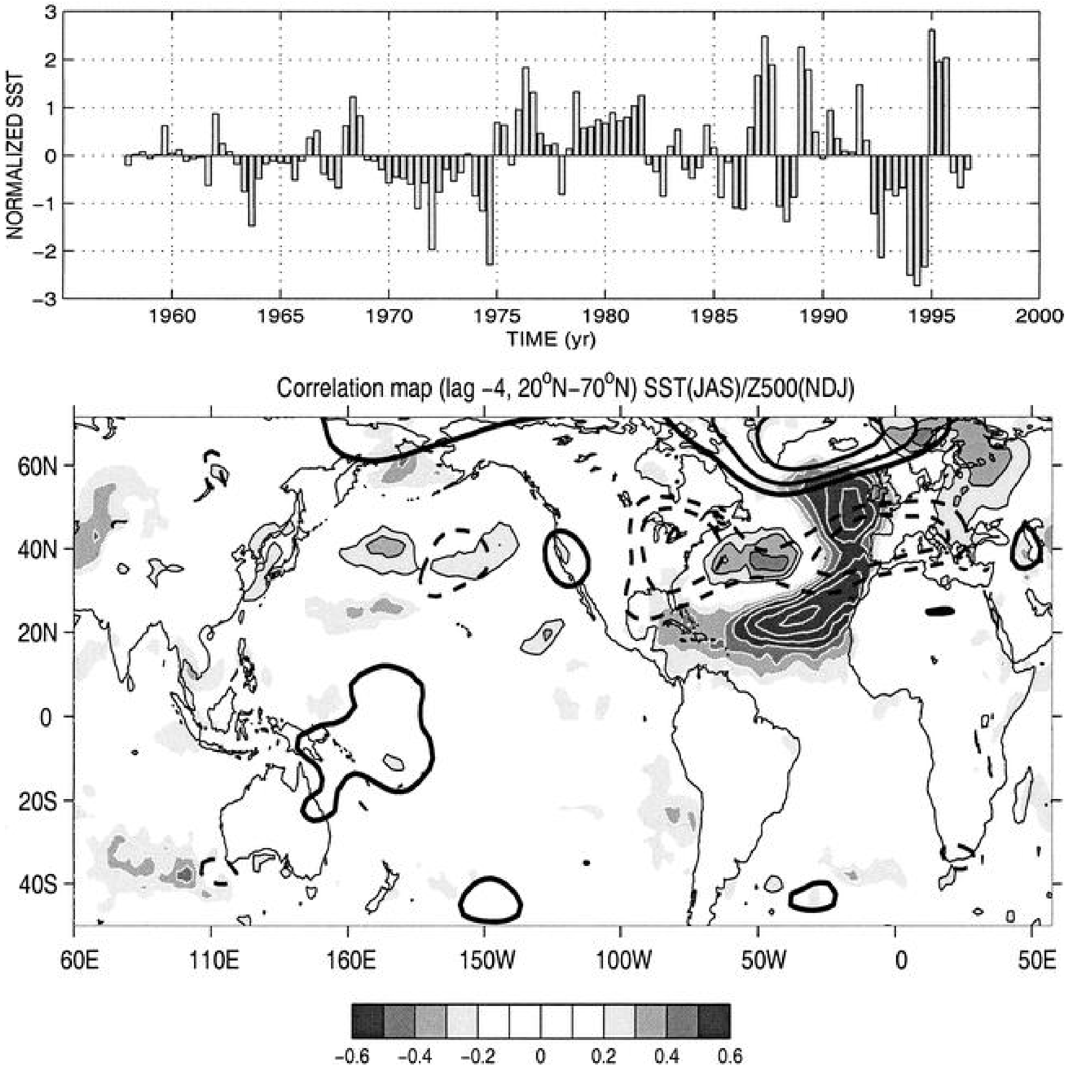

Figure 1: The leading MCA mode between North Atlantic (20-70N) summertime (JJA) SST and early winter (NDJ) 500hPa geopotential height (GPH) from Czaja and Frankignoul (2002). Top panel shows normalized SST timeseries; each year consists of three vertical bars corresponding to the months July-August-September. Bottom panel shows correlation maps of GPH (thick black contours, interval=0.1) and SST onto the SST timeseries. Only correlations with amplitude ≥ 0.2 *are indicated.*

The absence in Fig. 1 of significant correlations with SST variations outside the Atlantic basin is consistent with the suggestion that this mode is evidence of an Atlantic Ocean influence on climate. Whether the whole SST pattern, or only parts of it, are important for forcing the atmosphere cannot be inferred from this analysis. In addition, it should be noted that - because of the 4 month lag employed - we cannot infer that the atmosphere responds to the exact SST pattern shown in Fig. 1; rather, it must respond to whatever ocean conditions develop from this pattern in the subsequent autumn and early winter. We may anticipate a significant degree of persistence in the pattern but the evolution will also be influenced by, for example, advection in the ocean and air-sea fluxes.

Rodwell and Folland (2002) performed a similar analysis to Czaja and Frankignoul (2002), and again found a significant association between the wintertime North Atlantic Oscillation and preceding anomalous conditions in the Atlantic Ocean. They used monthly SST data rather than 3 month means and found that a pattern of SST in the preceding May provided the best predictor of the subsequent wintertime (DJF) NAO, yielding a correlation skill of ~ 0.4. This level of skill is statistically significant and suggests that an understanding of the Atlantic influence on climate could be usefully exploited in seasonal forecasting.

3 Evidence from Atmospheric GCM Studies of an Atlantic Ocean Influence on Climate

3.1 Multiyear simulations

Further evidence that the Atlantic Ocean has a significant influence on climate variability comes from studies in which atmospheric General Circulation Models (henceforth AGCMs) are forced with a reconstruction of historical variations in SST. Ensemble simulations, in which individual ensemble members share common SST forcing but differ in respect of their initial conditions, enable the oceanic influence on climate variability to be distinguished from variability generated within the atmosphere itself. Furthermore, unlike the analyses of observations, these model studies can be used to identify simultaneous, rather than leading, patterns of SST forcing.

Several studies, starting with Rodwell et al (1999), have shown that AGCM ensemble simulations have some skill in reproducing the historical record of variability in the NAO. These studies suggest a significant oceanic influence on North Atlantic climate, but there is some debate about which regions of the ocean are most important. Rodwell et al (1999) emphasised the role of SST anomalies in the Atlantic basin, whereas Hoerling et al (2001) suggested that the rising trend in the NAO index that was observed in the later part of the twentieth century was primarily a response to SST changes in the tropical Pacific and Indian Oceans, with little role for the Atlantic. There is a need to understand these apparently conflicting claims. A second issue was raised by Bretherton and Battisti (2000), who pointed out that a significant correlation (as shown by, e.g., Rodwell et al) between the observed NAO index and an NAO index computed from the ensemble mean of a set of AGCM simulations does not necessarily imply, as it may appear to do, that the oceanic forcing of the NAO (which may be termed the "signal") is strong by comparison with the contribution of internal atmospheric variability (which may be termed the "noise"). The reason is that ensemble averaging has the effect of inflating the signal-to-noise ratio relative to that found in a single ensemble member. Since it is the signal-to-noise ratio in a single ensemble member that is the best guide to the potential predictability associated with an oceanic influence it is important that we consider this quantity when when gauging the physical - and practical - significance of any results.

Sutton and Hodson (2002, hereafter SH02) analysed the latest set of ensemble ACGM simulations performed at the Hadley Centre with the HadAM3 model. This new ensemble extended over the period 1871-1999, considerably longer than the post-World War II period on which previous studies have been based. An additional difference from previous work was the use of an optimal detection methodology (Venzke et al, 1999) to identify the ocean forced signals. This approach, which is based on an analysis of signal to noise ratios, is attractive because it provides an objective way to identify which regions of the ocean are most important for forcing the atmosphere.

apologies Fig. 2, taken from SH02, shows the leading mode of SST-forced variability in North Atlantic wintertime MSLP. The signal-to-noise ratio associated with this mode is 0.64 ± 0.03. The MSLP pattern exhibits a dipole over the North Atlantic that has similarities to the NAO pattern. The timeseries displays interannual variability that appears to be superposed on a much longer timescale, multidecadal, variation. The SST pattern, which is obtained by regression on the timeseries, shows the highest fraction of variance explained in the tropical North Atlantic (TNA) region; this suggests that SST in the TNA region may have the dominant role in forcing this mode. Note that, consistent with the observational analyses, the sign of the association is that positive SST anomalies in the TNA region are associated with a negative NAO index.

As part of the EU-funded PREDICATE project the same analysis as shown in Fig 2 was carried out on ensemble simulations with three other atmosphere models: ECHAM4, ARPEGE AND ECHAM5. In two of the models, ARPEGE and ECHAM5, the leading mode of SST-forced variability has similar characteristics to those found in HadAM3. In the other model, ECHAM4, the dominant mode is associated with the response to ENSO. It appears, for reasons that are unclear, that the influence of ENSO on the North Atlantic region is comparatively stronger in the ECHAM4 model than in the other three.

A prominent feature of the timeseries shown in Fig. 2 is the presence of two timescales: interannual variability appears to be superposed on a much longer timescale, multidecadal, variation. The presence of two timescales invites the application of a filter to separate out the high and low frequency variability. Fig. 3 shows the leading mode of SST-forced low frequency variability in North Atlantic wintertime MSLP. The MSLP pattern is very similar to that seen in Fig. 2, while the timeseries shows multidecadal fluctuations with a prominent maximum around 1960, and a prominent minimum in the late twentieth century. The SST field shows anomalies of one sign across the whole North Atlantic with weaker negative anomalies in the South Atlantic and in the Indian Ocean. The pattern of SST anomalies in the Atlantic, together with the multidecadal timescale, suggests a link to the Thermohaline Circulation (THC). Delworth and Mann (2000) argued for the existence of a THC-driven “Atlantic Multidecadal Oscillation”. Our results lend weight to this suggestion, and support in particular the idea that THC induced variations in Atlantic SST can modulate the NAO on multidecadal timescales. (In this respect, we disagree to some extent with the suggestion of Hoerling et al, that the dominant oceanic forcing of the NAO is from the Indo-Pacific, but see SH02 for further discussion). The obvious implication is that, if it proves possible to predict variations in the THC, it may also be possible to predict some of the multidecadal variability in North Atlantic / European climate.

SH02 also analysed the oceanic forcing of high frequency (interannual-to-decadal) variability in North Atlantic climate. On these timescales two influences were identified: 1) an influence of ENSO, and 2) an influence of Atlantic SST. Consistent with Fig. 2 and with other research (Sutton et al, 2002; Cassou and Terray, 2001), the latter influence appears to be associated primarily with SST anomalies in the TNA region, and with an atmospheric response that projects on the NAO. Comparison of the atmospheric responses associated with the two oceanic influences suggests that, over the North Atlantic, there may be some competition between them. Which influence dominates will depend partly on the magnitude of the SST anomalies in each forcing region. In addition, however, SH02 present evidence that the competition may be modulated by the multidecadal variability in Atlantic SST. They suggest, in other words, that the oceanic influence on interannual variability in North Atlantic climate was *nonstationary* in the period analysed (1871-1999). A possible theory for this nonstationarity is discussed in the next section.

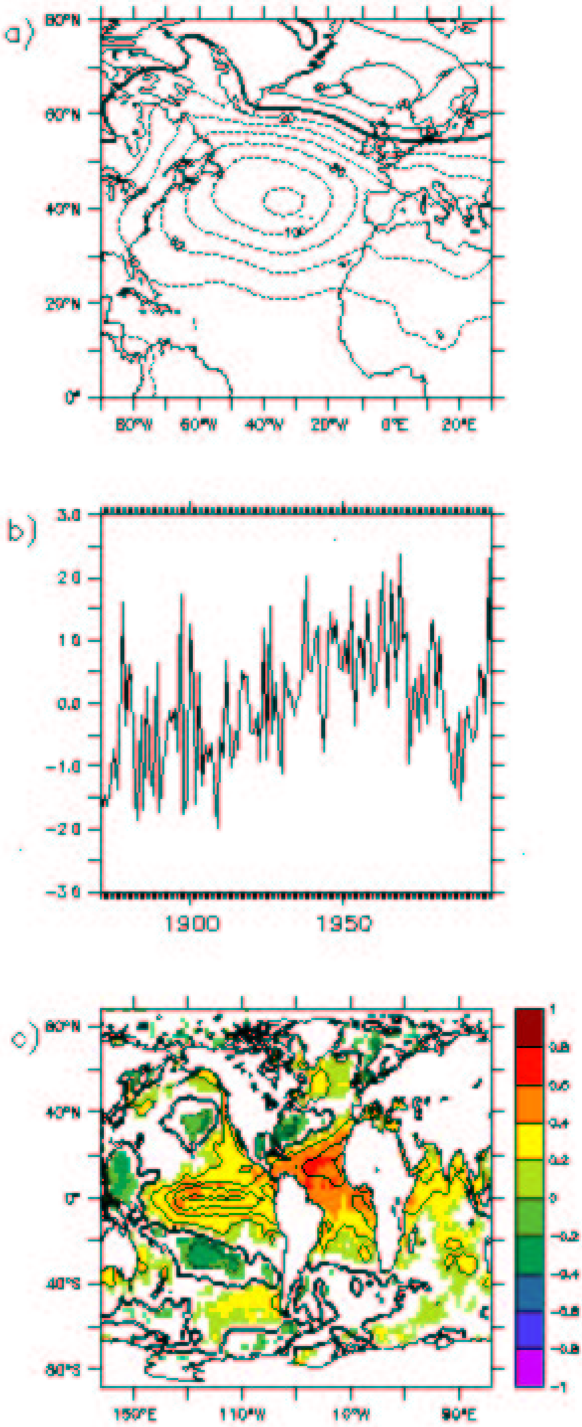

Figure 2: The leading mode of SST-forced MSLP variability in winter (DJF) over the N. Atlantic Region: in a) contours show mean sea level pressure in Pa; b) shows normalised time series; c) shows the SST patterns derived by regression on the time series shown in b. Contours show the value of regression coefficient at each point (contour interval is 0.1 K), shading shows the square-root fraction of the SST variance explained, multiplied by the sign of the regression coefficient. White regions are those where the regression coefficient is not significant at the 1.5σ level. From Sutton and Hodson (2002).

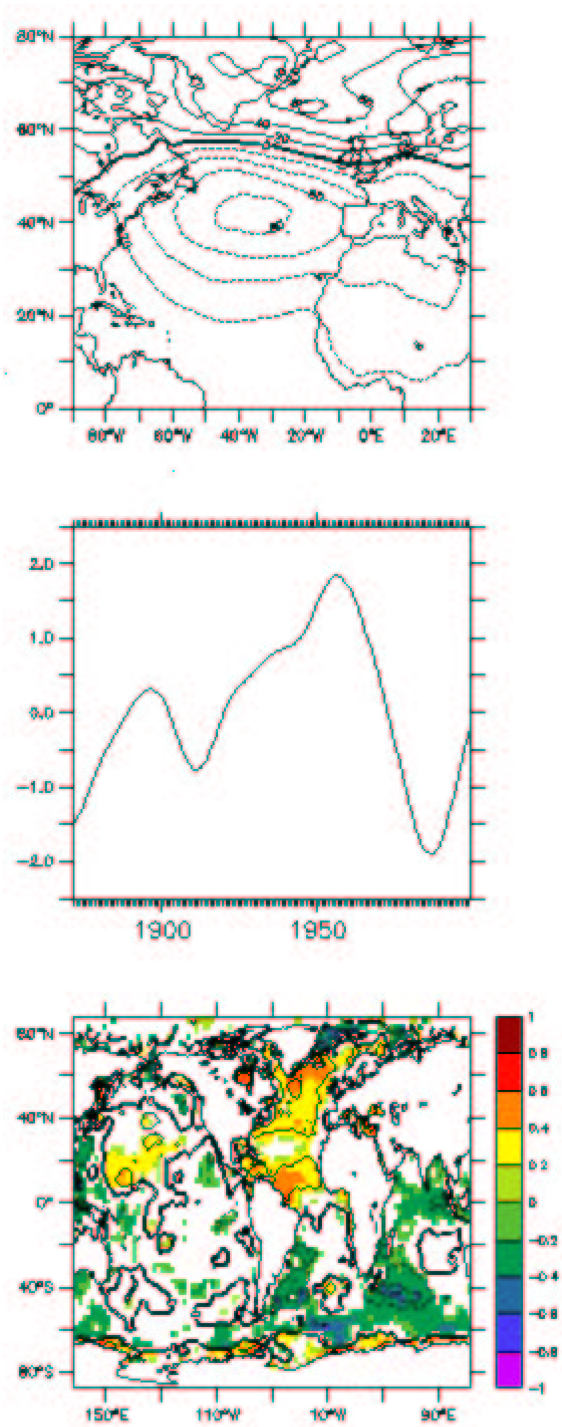

Figure 3: As Fig 2 but for the leading mode of SST-forced variability of detrended, low-pass filtered, MSLP.

3.2 Case studies of individual winters

The analyses discussed in the previous section help to identify which aspects of ocean variability have most influence on the atmosphere. However, a limitation with such studies is that, because SST varies everywhere in the oceans, it is difficult to isolate the specific influence of one region such as the Atlantic. To achieve such isolation, further experiments are needed. Mathieu et al (2002) carried out AGCM experiments (again using the HadAM3 model) that enable direct identification of the Atlantic influence. They performed a control experiment ("GLOB") forced with the global Reynolds SST over the period 1985-2001, and a second experiment ("IPAC") forced with the same SST in the Indo-Pacific basin but with climatological SST in the Atlantic basin. For both experiments ensembles of 10 simulations were performed, and analysis of the differences between the GLOB and IPAC experiments provides information about the Atlantic influence. We term these differences "ATL".

Mathieu et al analysed the role of Atlantic conditions during 6 ENSO events. Fig. 4 shows results for two El Nino winters: 1987/88 and 1991/92. Individual panels show the simulated ensemble mean anomalies in 500hPa geopotential height (GPH) for GLOB, IPAC and ATL, and shading indicates significance at the 95% level. It is clear that, in both winters Atlantic SST anomalies exerted a significant influence on the atmosphere. Moreover, it appears that in 1987/88 the Atlantic influence dominated the influence of the Indo-Pacific. In this winter the pattern of GPH anomalies seen in GLOB is much closer to that found in ATL than that found in IPAC. Interestingly, the ATL GPH pattern for 91/92 is almost opposite to that found in 87/88.

A critical question, of course, is what is the mechanism via which Atlantic SST anomalies induce the atmospheric responses shown in Fig. 4? Mathieu et al argue that the mechanism involves the influence of SST anomalies in the tropical Atlantic region on local convection, and the subsequent excitation of a Rossby wave response that propagates into midlatitudes. Fig. 5 shows the ATL precipitation anomalies for the two winters 87/88 and 91/92. For winter 87/88 the figure shows a dipole pattern of precipitation anomalies, which implies a southward shift of the ITCZ, over the tropical Atlantic ocean, and an increase in precipitation over eastern south America. During this winter there were positive SST anomalies in the tropical Atlantic ocean with the largest anomalies located just south of the ITCZ (not shown); thus it is likely that the precipitation anomalies arise as a direct, local, response to the anomalous SST. This hypothesis is further supported by the results for winter 91/92; at this time negative SST anomalies were located in the tropical Atlantic region, and Fig. 5 shows a reduction in precipitation over the tropical Atlantic ocean and eastern South America.

Associated with the precipitation anomalies shown in Fig. 5 will be anomalous diabatic heating and a Rossby wave source (eg Hoskins and Ambrizzi 1993). Ambrizzi and Hoskins (1997) showed that for a zonally extended source, such as that associated with the ITCZ anomalies shown in Fig 5, theory predicts the excitation of Rossby waves that propagate meridionally into midlatitudes, and exhibit a zonal scale similar to that of the source. Inspection of Fig 4 shows that the characteristics of the ATL GPH anomalies are in line with these theoretical predictions, thus supporting our hypothesis concerning the mechanism of Atlantic SST influence.

An interesting aspect of this mechanism is that it suggests that the influence on climate of interannual variability in the tropical Atlantic ocean may be modulated by variability on longer timescales. The reason is that the sensitivity of tropical convection to SST is highly nonlinear, hence the magnitude of the convective response will depend not simply on the magnitude of the SST anomaly but also on the absolute SST. If the "background" SST varies on multidecadal timescales as a consequence of, e.g., variability in the Thermohaline Circulation, then we might expect that the strength of the atmospheric response to be correspondingly modulated. This idea offers a possible explanation for the nonstationarity of the oceanic influence on North Atlantic / European climate that was found by SH02 and mentioned at the end of the previous section.

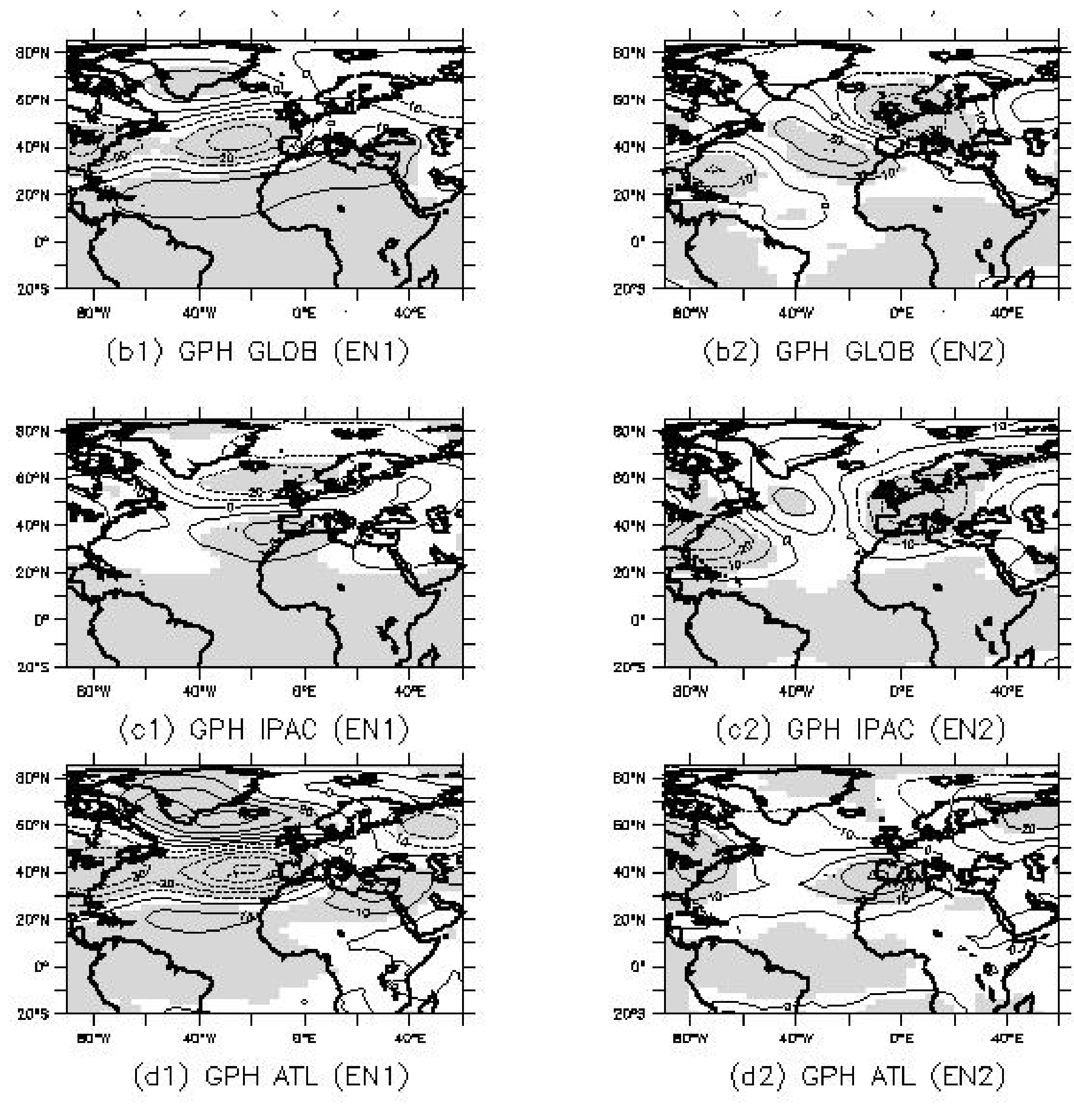

Figure 4: DJF Ensemble mean geopotential height anomalies at 500mb for the winters of 1987/88 (left panels) and 1991/92 (right panels). Results are from the GLOB experiment (top panels), the IPAC experiment (middle panels) and ATL - see text for details. Shading indicates significance at the 1.5σ level. From Mathieu et al, 2002

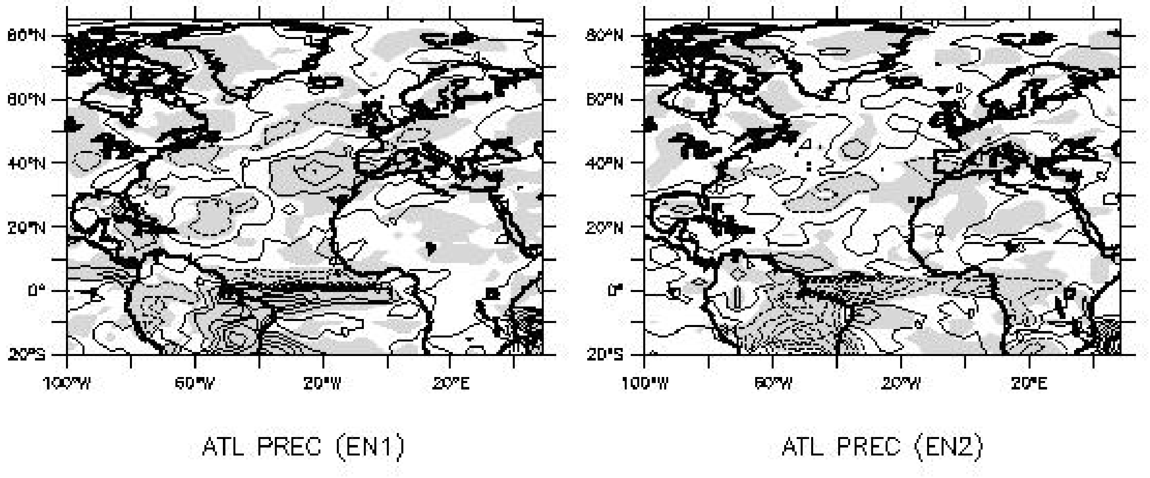

Figure 5: As fig 4 but for ATL precipitation anomalies. Left panel shows DJF 1987/88; right panel shows DJF 1991/92.

4 Conclusions

Evidence from observations and atmosphere model simulations suggests that the Atlantic Ocean exerts a significant influence on the winter climate of the North Atlantic / European region, influencing both interannual variability and longer timescale, multidecadal, variability. The evidence suggests that the atmospheric response to variability in the Atlantic Ocean has a significant projection on the North Atlantic Oscillation (NAO) pattern. The mechanism has yet to be fully explained but model results suggest that a key part is likely to be the impact on local convection of SST anomalies in the tropical Atlantic region, and the consequent excitation of a Rossby wave response that propagates into midlatitudes.

There is an obvious need for further research to elucidate the Atlantic ocean influence on climate, and the consequences for seasonal and longer timescale climate forecasting. At the level of basic understanding, the highest priority must be to gain more insight into the mechanism of oceanic influence including such aspects as the nonlinearity of the atmospheric response (e.g. as mentioned at the end of Section 3.2; see also Terray and Cassou, 2002). At the interface of understanding and practical application, the highest priority must be to investigate how the insights gained from observational analyses and atmosphere model studies are relevant to understanding the behaviour, and especially the predictability, of the coupled ocean-atmosphere system. Research in progress suggests that current coupled models are deficient in reproducing the observed relationships between Atlantic ocean conditions and climate, and that forecast systems based on such models may therefore underestimate climate predictability.

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