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Influence of Atlantic SST anomalies on the atmospheric circulation in the Atlantic-European sector

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Abstract
Recent studies of observational data suggest that Sea Surface Temperature (SST) anomalies in the Atlantic Ocean have a significant influence on the atmospheric circulation in the Atlantic-European sector in early winter and in spring. After reviewing this work and showing that the spring signal is part of a global air-sea interaction, we analyze for comparison an ensemble of simulations with the ECHAM4 atmospheric general circulation model in T42 resolution forced by the observed distribution of SST and sea ice, and a simulation with the ECHAM4/OPA8 coupled model in T30 resolution. In the two cases, a significant influence of the Atlantic on the atmosphere is detected in the Atlantic-European sector. In the forced mode, ECHAM4 responds to SST anomalies from early spring to late summer, and also in early winter. The forcing involves SST anomalies not only in the tropical Atlantic, but also in the whole tropical band, suggesting a strong ENSO influence. The modeled signal resembles that seen in the observations in spring, but not in early winter. In the coupled mode, the Atlantic SST only has a significant influence on the atmosphere in summer. Although the SST anomaly is confined to the Atlantic, the summer signal shows some similarity with that seen in the forced simulations. However, there is no counterpart in the observations.

Key words *air-sea interaction – climate variability – Atlantic SST anomalies*

1. Introduction

Until recently, it had not been established from the observations whether SST anomalies in the North Atlantic have a significant effect on the North Atlantic Oscillation (NAO) and the other main atmospheric patterns in the Atlantic-European sector. To a large extent, this resulted from the difficulty in separating cause and effect. Indeed, the dominant air-sea interaction at mid latitudes is the forcing of the ocean by the atmosphere, which acts on the monthly and longer time scales as a stochastic forcing and generates large-scale Sea Surface Temperature (SST) anomalies (Frankignoul and Hasselmann, 1977). In the observations and in coupled models, this one-way interaction tends to mask the impact that the extra-tropical ocean may have on the atmosphere. Nonetheless, by studying the co-variability between observed SST and surface heat flux anomalies in the North Atlantic when the ocean leads by more than the atmospheric persistence, Frankignoul *et al.* (1998) showed that existing SST anomalies are damped by the turbulent surface heat flux. The heat flux feedback implies that existing mid-latitude SST anomalies exchange a substantial amount of

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energy with the atmosphere (Frankignoul and Kestenare, 2002).

In a study based on the COADS observations and the NMC-NCAR archives from 1952 to 1992, Czaja and Frankignoul (1999) used a Maximum Covariance Analysis (MCA) to investigate the lagged relations between North Atlantic SST anomalies and the tropospheric circulation. As the atmospheric dynamics strongly vary with season, they stratified the analysis by sets of three successive months and found a predictive skill for atmospheric anomalies in two seasons. In late spring, a circulation anomaly over the Northwest Labrador Sea was found to be associated with the dominant mode of North Atlantic SST variability (the so-called SST anomaly tripole) during the preceding winter. It was more clearly seen in the mid-troposphere than at sea level and appeared to be related to anomalous surface heat exchanges. In addition, an early winter signal strongly resembling the NAO was found to be associated with SST anomalies east of Newfoundland and in the eastern subtropical North Atlantic during the preceding summer. The analysis was repeated and extended to the whole Atlantic domain by Czaja and Frankignoul (2002, hereafter CF), using the more accurate reanalysis data from NCEP. Using lagged MCA, they confirmed the nature and statistical significance of their earlier findings. In addition, a separate analysis was done with only mid-latitude or tropical Atlantic SST anomalies, so that the main oceanic regions of influence could be better determined. The early winter NAO-like signal has been discussed by CF. As reviewed in Section 2, it is primarily linked to a horseshoe-like SST anomaly in the North Atlantic. The late spring atmospheric signal seemed to be primarily forced by SST anomalies in the tropical Atlantic, but it was not discussed in CF. It is shown in Section 2 that SST anomalies in the North Atlantic mid latitudes, the tropical Pacific and the Indian oceans also contribute, so that the signal reflects a global air-sea interaction.

Sensitivity studies with atmospheric General Circulation Models (GCMs) generally show that idealized North Atlantic SST anomalies have some influence on the wintertime circulation, but the results are model-dependent (see Robinson, 2000, and Kushnir *et al.*, 2002 for recent reviews). By using an ensemble of GCM simulations forced by global SST and sea-ice distribution during the last decades, Rodwell *et al.* (1999) and Latif *et al.* (2000), among others, were able to reproduce some of the low frequency variability of the NAO. However, the former argued that in HadAM2b the bulk of the oceanic influence was coming from the North Atlantic SST anomaly tripole, while the latter suggested that it was mostly coming from the tropical Pacific in ECHAM4. A more detailled investigation of the response of ECHAM4 to the observed SST changes is given in Section 3. Finally, the Atlantic air-sea interactions in the SINTEX ECHAM4/OPA8 coupled simulation are discussed in Section 4. The results are summarized in Section 5.

2. Observed impact of Atlantic SST anomalies

To investigate how the atmospheric circulation is related to SST anomalies on the seasonal scale, CF used monthly anomaly fields from the NCEP-NCAR reanalysis (Kalnay *et al.*, 1996) over the period 1958-1997, after subtracting a third-order polynomial to remove the trends and low frequencies. The main technique was a lagged MCA based on a singular value decomposition of the covariance matrix (estimated with monthly anomalies binned into groups of 3 months) between two variables at a given time lag. Robustness was assessed by testing the statistical significance of the Squared Covariance (hereafter SC) and the correlation, using a moving blocks bootstrap approach.

The influence of the North Atlantic SST anomalies on the atmospheric circulation is well described by the MCA of SST and geopotential height anomalies at 500 hPa (thereafter Z500) in the domain 20°N-70°N, 100°W-20°E, while the influence of the tropical Atlantic SST anomalies is best seen in the MCA of SST between 20°S and 20°N and Pan-Atlantic Z500 anomalies (20°S-70°N, 100°W-20°E). Figure 1, from CF, shows the SC of the first MCA mode as a function of season and lag. Only the first mode of the MCA is significant when the ocean leads the atmosphere.

The largest SC occurs when the atmosphere is in phase with or leads SST by one month, as predicted by the stochastic climate model (Frankignoul and Hasselmann, 1977). Significant SCs (indicated by shading in fig. 1) are also found for the atmosphere in early winter when the North Atlantic SST anomalies lead by up to 5 or 6 months, with the largest skill in November-December-January (NDJ). As discussed in CF and illustrated in fig. 2, the atmospheric maximum covariance pattern is the NAO. At lag 0 and 1 (ocean follows), the results show that the NAO forces the North Atlantic SST anomaly tripole. At negative lags (ocean leads), they show that the NAO is significantly associated with a horseshoe-like SST anomaly in the North Atlantic, up to 5 or 6 months in advance. In view of the short atmospheric response time, this reflects an interaction between the NAO and the horseshoe SST anomalies that takes place during late fall or early winter. The SST influence can be seen several months in advance because the SST horseshoe pattern, a dominant summer mode, is very persistent. It can only be detected when SST precedes the atmosphere because otherwise the signal is masked by the strong natural variability of the NAO, and the resulting SST response. Because the NAO has a relatively long intrinsic time scale (Feldstein, 2000), the covariance may still in part reflect the atmospheric forcing of the ocean when SST leads by 1 month. This contributes to the low statistical significance and the mixture of tripole and horseshoe pattern seen at lag –1 in fig. 2. As shown in CF, the relatively low SC at lag –2 results from an interference with a remote forcing of the early winter NAO by SST anomalies in the tropical Atlantic, which corresponds to the significant SC seen in fig. 1 (bottom) for NDJ.

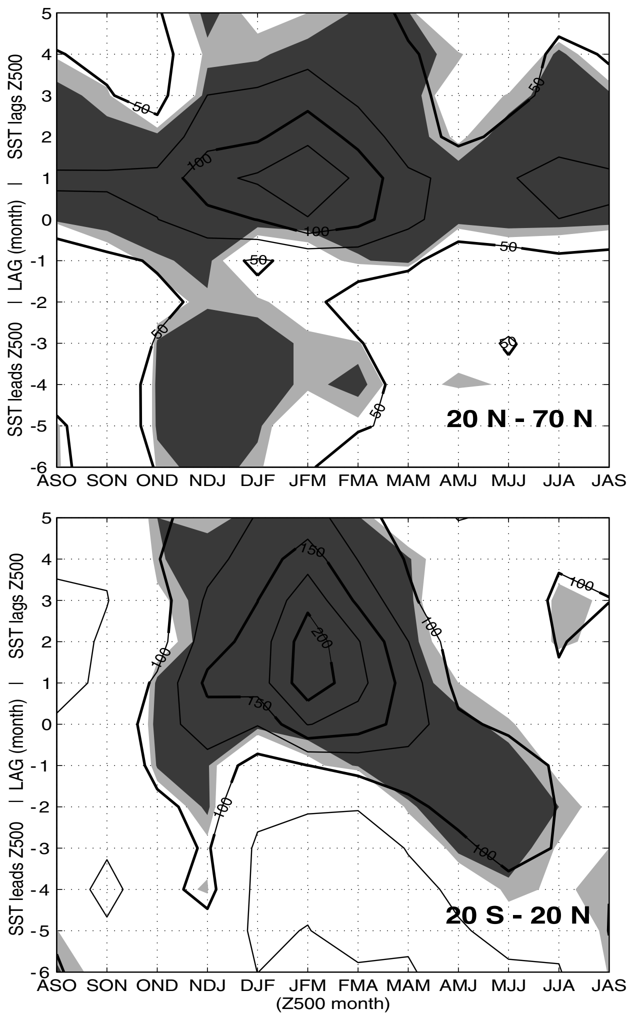

Fig. 1. Squared Covariance (SC) as a function of season and lag of the first MCA mode between (*top*) North Atlantic SST and Z500 anomalies at mid latitudes (20°N -70°N) and (*bottom*) tropical SST (20°S-20°N) and Pan-Atlantic Z500 anomalies (20°S-70°N). The SC is dimensionless, but the shaded area indicates where it is statistically significant at the 5% and 10% level (dark and light shading, respectively). From Czaja and Frankignoul (2002).

Although an influence of North Atlantic SST anomalies onto the spring atmospheric circulation was detected in Czaja and Frankignoul (1999), no significant co-variability is found in the NCEP reanalysis when it is limited to the 20°N-70°N domain (fig. 1, top). On the other hand, the covariance between tropical Atlantic SST and geopotential height is highly significant throughout spring (fig. 1, bottom). Starting in February-March-April (FMA), SST anomalies significantly co-vary with geopotential height anomalies up to 4 months later. The SST anomaly pattern can be seen in the global correlation map in fig. 3 of SST in MAM (top) and Z500 in MJJ (bottom) with the MCA-SST time series at lag – 2. North of 20°N, the patterns resemble those in Czaja and Frankignoul (1999), where a tripole-like late winter SST anomaly was associated with a geopotential height anomaly in spring having its main center of action west of the Labrador Sea (note that the signal appears as first mode in

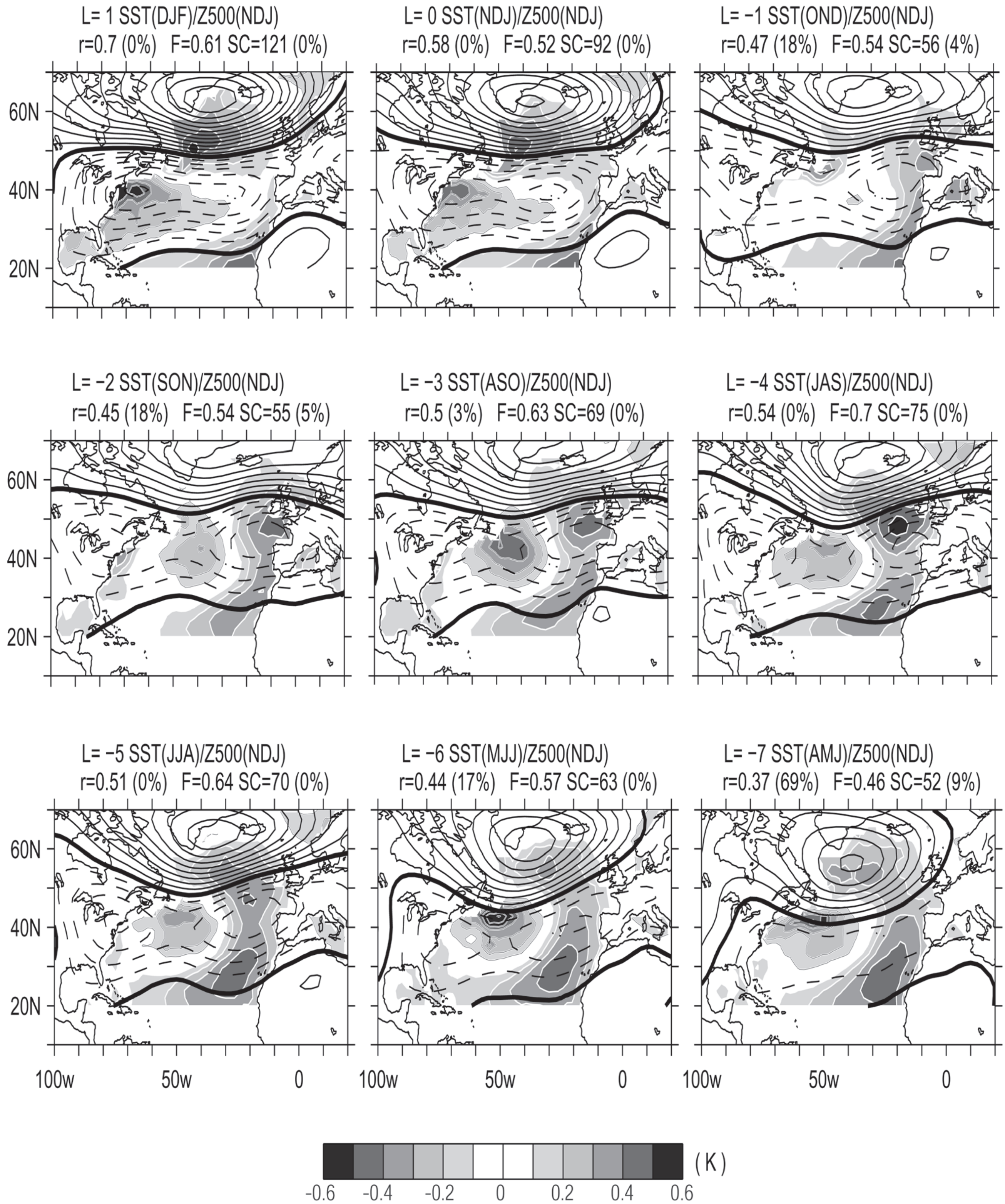

Fig. 2. Heterogeneous NDJ 500 hPa geopotential (contour interval 5 m with negative values dashed) and homogeneous SST (gray shading in K with white contours for positive values and black contours for negative values) covariance maps for the first MCA mode at various lags (SST leads at negative lag). The correlation *r* between the MCA time series, the SC fraction *F*, and the SC are indicated. The percentages in parentheses give the estimated significance level. From Czaja and Frankignoul (2002).

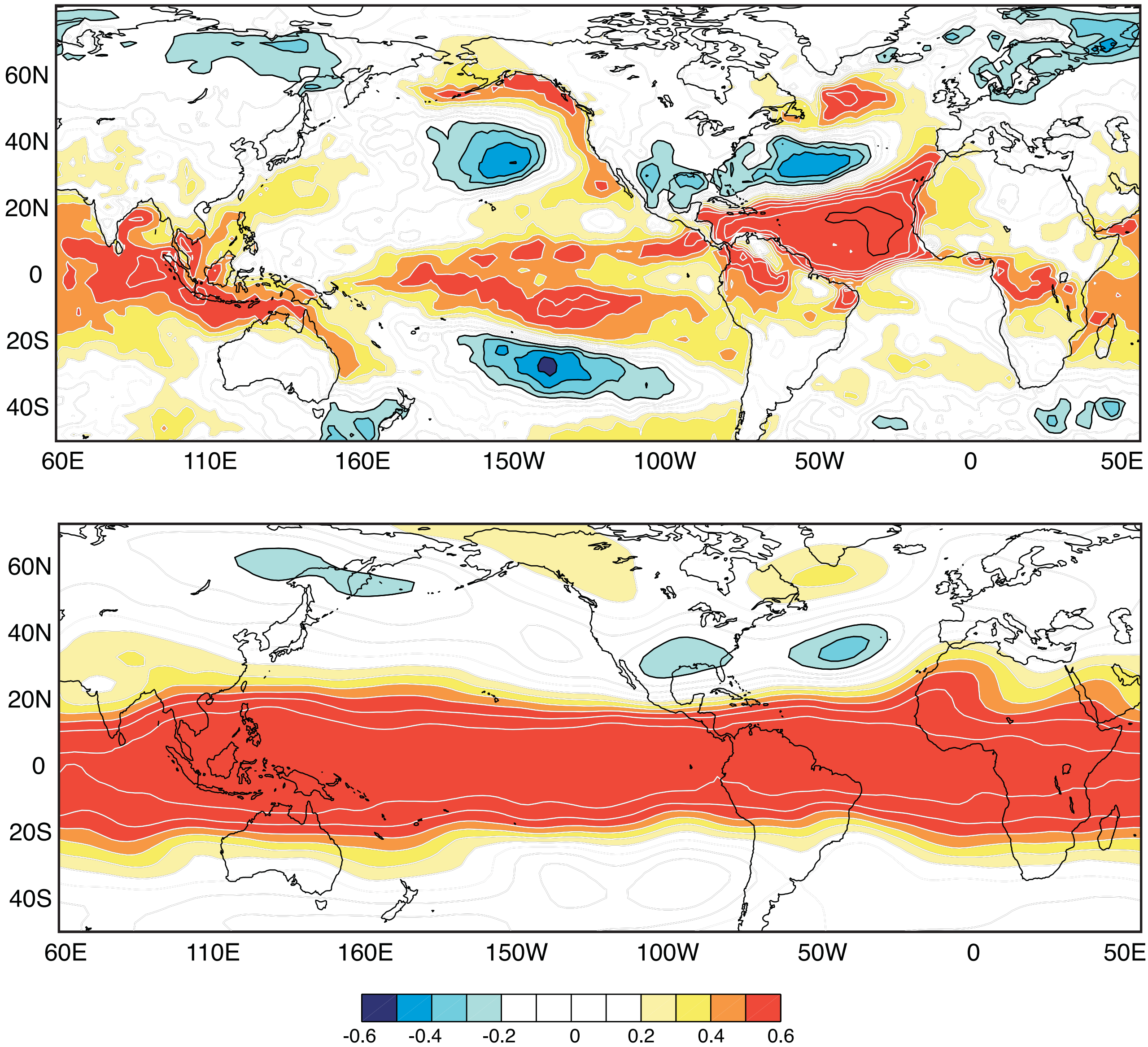

Fig. 3. Correlation of SST anomalies in MAM (*top*) and Z500 anomalies in MJJ (*bottom*) with the SST time series from the MCA at lag –2 between tropical Atlantic SST (20°S-20°N) and 500 hPa Pan-Atlantic geopotential height (20°S-70°N) in MJJ. Only correlations with amplitude ≥ 0.2 are indicated. White contours are for positive values and black contours for negative values.

the 20°-70°N MCA, but with low statistical significance). The correlation map shows that the southern lobe of the SST anomaly tripole is very strong in the tropical Atlantic down to the equator. In addition, although largest in the Atlantic, the tropical SST anomaly pattern extends to the Pacific and Indian oceans, with SST anomalies of the opposite polarity in the North and South Pacific. The SST pattern thus combines an El Niño-like SST anomaly with the North Atlantic tripole. In the atmosphere, there is a highly significant, zonally-symmetric geopotential height anomaly in the tropical band, in addition to the mid-latitude signal in the American-Atlantic sector. Note that the correlation is high in the Tropics because of the small natural variability of the atmosphere while it is small at mid latitudes where the natural variability is large, although the extratropical signal is much larger and would stand out in a regression map (see Czaja and Frankignoul, 1999). Nonetheless, figs. 1 and 3 suggest that the main interaction in spring takes place between SST in the tropical band and the Hadley circulation.

3. Impact of prescribed SST anomalies on the Atlantic-European sector in ECHAM4

To investigate the sensitivity of the atmosphere to prescribed SST anomalies in an atmospheric GCM, we have considered the ensemble mean of six simulations with ECHAM4 in T42 resolution (Röckner *et al.*, 1992) made at the Max-Planck Institute für Meteorologie in Hamburg and forced by the observed SST and sea ice distribution during 1951-1994 (Latif *et al.*, 2000). In the simulations, the CO_2 concentration varies with time, as estimated from the observations. A MCA was carried out between SST in the North Atlantic (10°N-80°N) and Sea Level Pressure (SLP) in the European-Atlantic domain defined by 10°N-80°N and 90°W-45°E, after removing at each grid point a third order polynomial in order to reduce the influence of the low frequencies. As SST is prescribed and there is no need to distinguish between cause and effect, the MCA is performed without time lag between SST and SLP. This allows us to further increase the signal-to-noise ratio by considering seasonal mean anomalies instead of monthly ones as before. Statistical significance is estimated with a bootstrap approach, using 200 Monte Carlo permutations of the SLP sequence for each season.

Table I summarizes the results as a function of (running) season for the first two MCA modes. Note that the first mode is well separated if its SC fraction *F* is much larger than that of the second mode. Significant first modes are found from early spring (FMA) to late summer (JAS), and in late fall (NDJ). In spring and summer the first MCA mode is highly significant and well separated from the second mode. In NDJ the first two modes are significant, albeit at a lesser level, but they are poorly separated (comparable SC fraction). No significant co-variability is found in mid winter, although Latif *et al.* (2000) showed that the very low-frequency variability of the winter NAO was in part reproduced by the model. However, the SST influence was primarily

Table I. MCA for running seasonal mean Euro-Atlantic SLP and prescribed North Atlantic SST anomalies in ECHAM4 forced by the observed SST and sea-ice distribution in 1951-1994. The correlation *r* between the MCA time series, the SC fraction *F*, and the SC are indicated for the first (top) and second (bottom) modes. The percentages in parentheses give the estimated significance level. Bold, underlined values indicate significance at the 5% level.

	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
MCA1												
SC($*10^3$)	1.3	1.6	**2.6**	**2.4**	**1.6**	**1.2**	**1.1**	**0.8**	0.7	0.8	1.2	**1.6**
	(34%)	(38%)	**(2%)**	**(0%)**	**(0%)**	**(0%)**	**(0%)**	**(7%)**	(27%)	(32%)	(12%)	**(0%)**
r	0.48	0.38	0.46	**0.58**	**0.63**	**0.83**	**0.83**	**0.74**	**0.64**	0.51	**0.59**	**0.61**
	(48%)	(78%)	(11%)	**(0%)**	**(1%)**	**(0%)**	**(0%)**	**(0%)**	**(4%)**	(54%)	**(6%)**	**(2%)**
F	23%	26%	**42%**	**44%**	**35%**	**32%**	**30%**	24%	21%	19%	23%	28%
	(85%)	(78%)	**(5%)**	**(0%)**	**(3%)**	**(1%)**	**(2%)**	(47%)	(71%)	(88%)	(64%)	(20%)
MCA2												
SC($*10^3$)	1.0	1.0	0.7	0.6	0.5	0.4	0.4	0.6	0.6	**0.7**	**1.0**	**1.1**
	(16%)	(29%)	(37%)	(14%)	(37%)	(71%)	(52%)	(27%)	(20%)	**(6%)**	**(4%)**	**(2%)**
r	0.53	0.55	**0.63**	**0.67**	0.58	**0.66**	**0.62**	0.52	0.53	**0.66**	0.55	**0.61**
	(42%)	(18%)	**(4%)**	**(3%)**	(32%)	**(1%)**	**(8%)**	(40%)	(40%)	**(4%)**	(26%)	**(2%)**
F	18%	17%	11%	11%	10%	11%	12%	16%	17%	18%	19%	20%
	(52%)	(58%)	(88%)	(60%)	(90%)	(96%)	(96%)	(65%)	(55%)	(40%)	(36%)	(10%)

originating from SST anomalies in the tropical Pacific, and no trend had been removed. The interaction is thus not expected to show up in a MCA where the SST is limited to the Atlantic-European sector and a cubic trend has been removed. By comparing the ECHAM4 response and the observed atmospheric anomalies, Friederichs and Frankignoul (2002, submitted for publication) have shown that the correlation with the observed NAO looses significance as soon as a linear trend is removed. As the CO_2 concentration increases with time in the simulations, it cannot be decided whether the co-variability discussed in Latif *et al.* (2000) reflects anthropogenic or oceanic effects.

The spring patterns are illustrated in fig. 4, where the SLP (top), SST (middle), and Z500 (bottom) anomalies are regressed globally onto the SST time series, although the MCA was only performed between SST and SLP in the domain inside the box in the upper right corner. In the latter, the maps represent the heterogeneous and homogeneous maximum covariance patterns for the two variables, respectively, while elsewhere they are regression patterns. The SLP pattern seem to in part combine the NAO, the Pacific-North-American (PNA) pattern, and the Southern Oscillation. The Z500 signal is a zonally-symmetric warming in the Tropics and a dipole over the American-Atlantic sector that resembles the spring signal seen in the observations (fig. 3, bottom), except in the Northeastern Pacific. In the North Atlantic, the SST anomaly pattern resembles the SST anomaly tripole, but there is also an El Niño-like SST anomaly in the tropical Pacific and the Indian Ocean, so that the SST anomaly also resembles the global one seen in the observations (fig. 3, top). To investigate whether the mode exists independently from the El Niño-Southern Oscillation (ENSO) phenomenon, we performed the same MCA after removing some of the influence of ENSO on the SST and SLP anomalies in the European-Atlantic domain. This was done by a seasonally varying regression analysis, using the first two principal components of the tropical Pacific SST anomalies to define ENSO, as in Frankignoul and Kestenare (2002). After (linear) ENSO removal, no significant MCA mode could be found in FMA nor MAM. This suggests that, at least in the model, ENSO is mostly responsible for the spring co-variability seen in fig. 4. However, since up to 30% of the SST anomaly variance in MAM had been removed in the tropical Atlantic, it cannot be excluded that the tropical Atlantic SST significantly contributes to the atmospheric signal in fig. 4 via a SST structure that is directly linked to ENSO.

The co-variability illustrated in fig. 4 remains significant until the end of summer, but the patterns evolve. As illustrated for JJA in fig. 5, the SLP anomaly weakens in the North American-North Atlantic sector and over Europe, while strengthening over the Gulf of Mexico and in the South Pacific, whereas the Z500 signal looses significance poleward of about 40°. At the same time, the large SST anomaly amplitudes become increasingly limited to the tropical and subtropical North Atlantic. There remains some relation to Pacific and Indian SST anomalies that resemble a matured El Niño pattern, but the summer signal remains highly significant when the ENSO signal is removed (not shown). During summer the SST anomalies in the Atlantic thus seem to have some genuine influence in the model on the atmospheric circulation in the Atlantic sector at tropical and subtropical latitudes. However, no corresponding signal was found in the observations.

In late autumn/early winter, the SLP and SST anomalies show some co-variability in the European-Atlantic sector, but, even if significance is high for the first two MCA modes (table I), the maximum covariance patterns are difficult to interpret as they are poorly separated. As shown in fig. 6 (left), the Pacific SST seems to be again involved, and the first maximum covariance pattern for SST is essentially the same as in MAM. However, in NDJ it is linked to a strengthening of the NAO, rather than a weakening as in fig. 4, with a large amplitude over Europe. This supports the findings of Peng *et al.* (1995) that the atmospheric response to the same SST anomaly may be different, even of opposite sign, in different seasons and mean atmospheric conditions. The second mode (fig. 6, right) shows a tripole SST anomaly in the North Atlantic and La Niña conditions in the tropical Pacific, which is related to a high pressure anomaly extending over nearly the whole North Atlantic. When

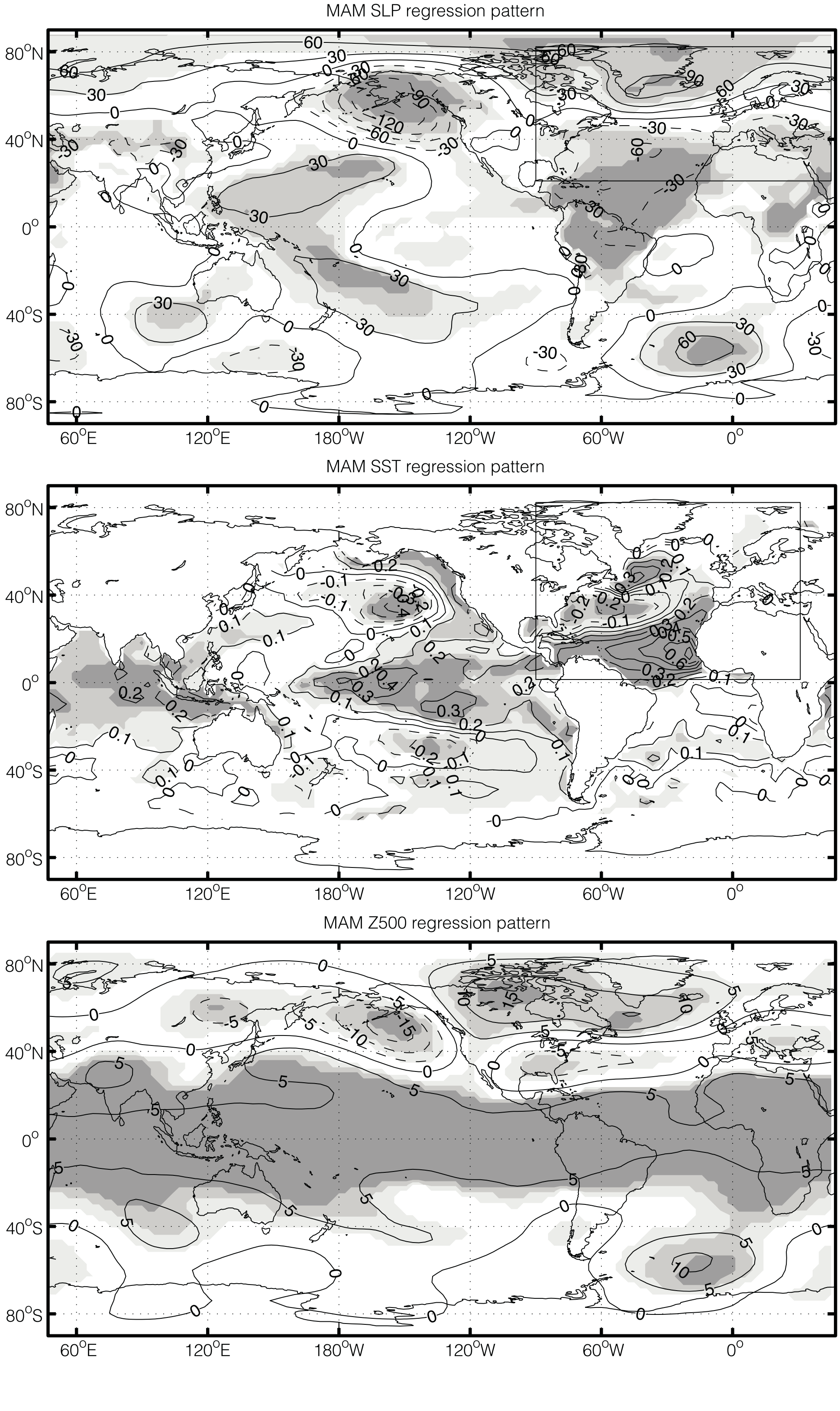

Fig. 4. Linear regression of global SLP (*top*), SST (*middle*), and Z500 (*bottom*) anomalies on the SST time series of the first MCA mode of Euro-Atlantic SLP and North Atlantic SST in the 1951-1994 simulations with ECHAM4 (MAM seasonal means). The box indicates the region used for the MCA. Shading indicates the 10%, 5%, and 1% significance levels. Contours are 30 Pa for SLP, 0.1 K for SST, and 5 m for Z500.

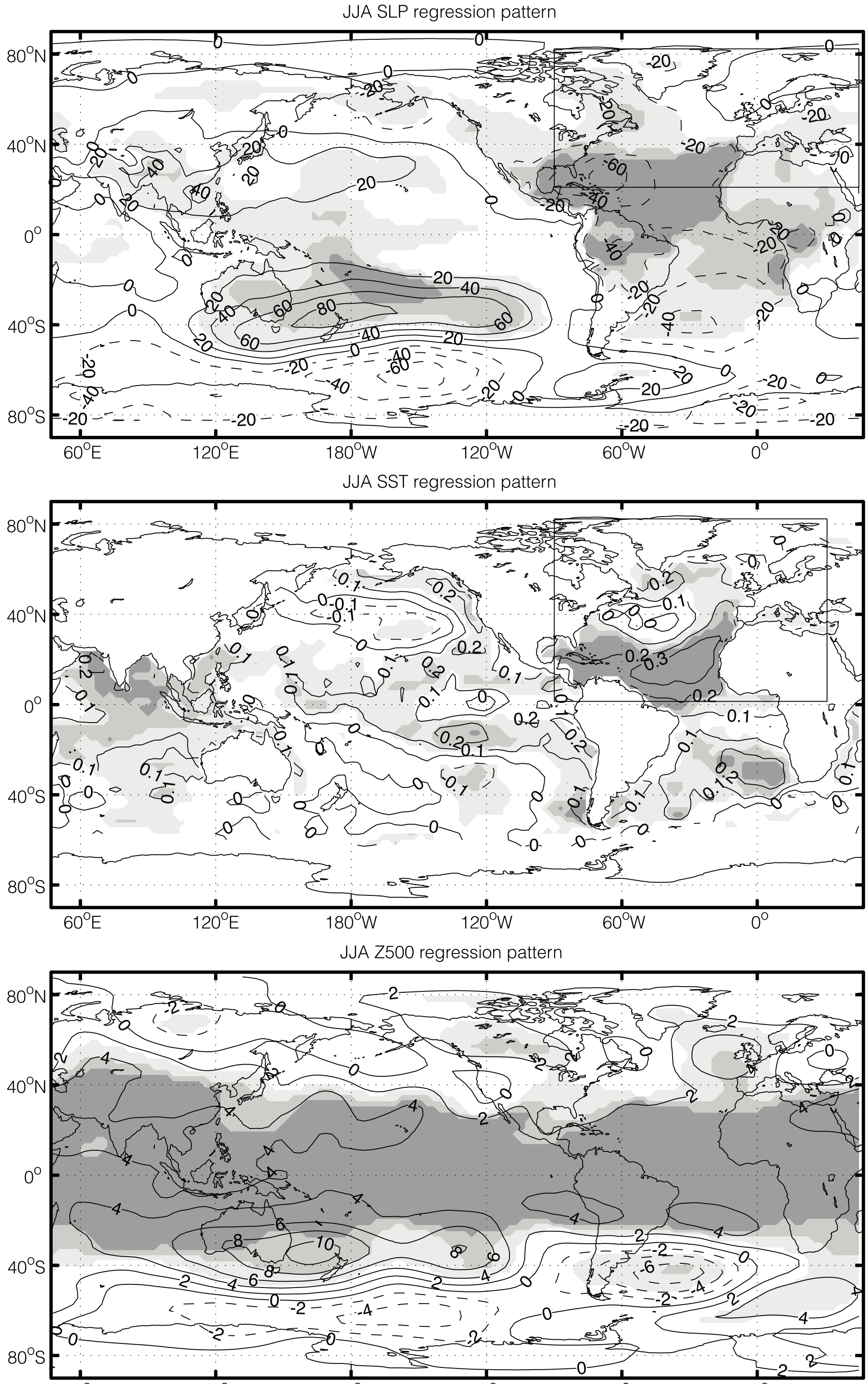

Fig. 5. As fig. 4, but for JJA seasonal means. Contours are 20 Pa for SLP, 0.1 K for SST, and 2 m for Z500.

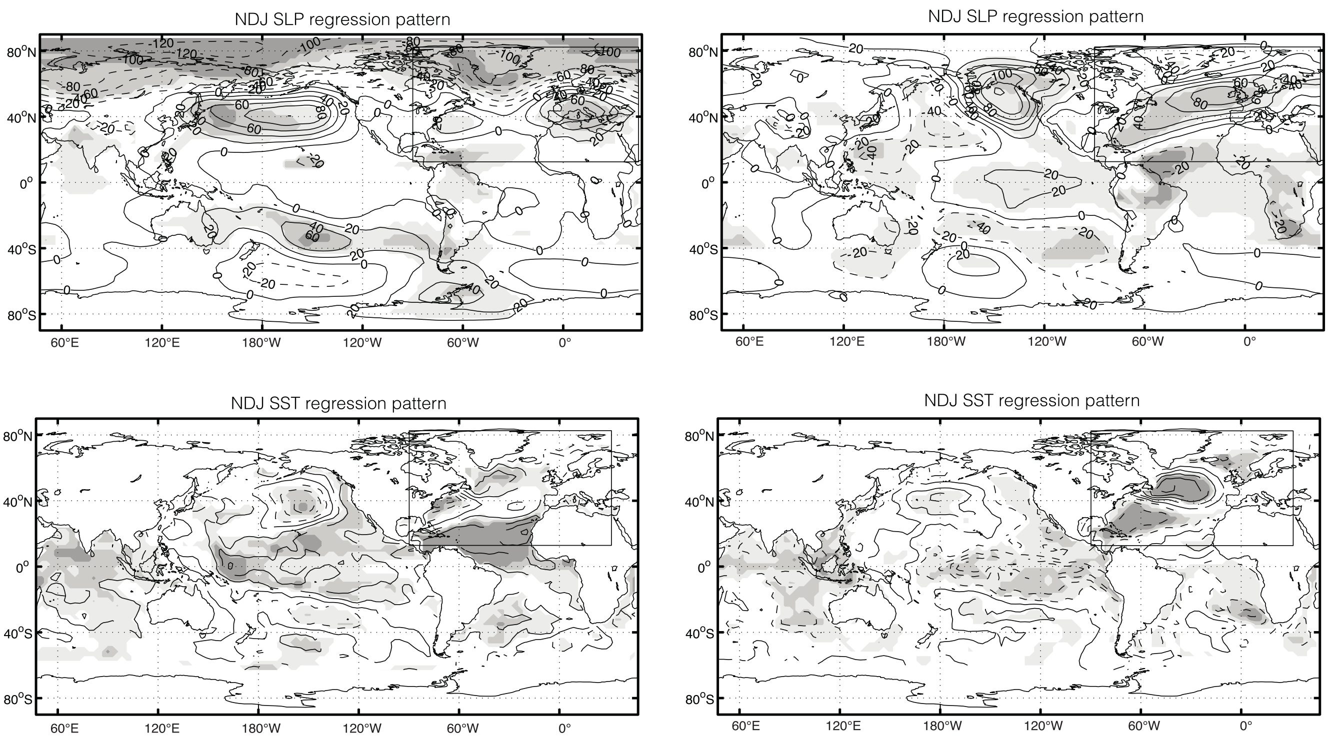

Fig. 6. As in fig. 4 (top two panels), but for the first (left) and second (right) MCA mode for NDJ seasonal means. Contours are 20 Pa for SLP and 0.1 K for SST.

ENSO is removed, only the first MCA mode in NDJ remains significant, with a stronger SST signal in the North Atlantic but little change in SLP (not shown), which suggests that some of the SLP signal in fig. 6 comes from Atlantic SST influence. However, the modulation of the NAO strength that can be recognized in NDJ is not associated in ECHAM4 with the North Atlantic horseshoe anomaly found in the observations (fig. 2), and the link between tropical Atlantic SST and SLP anomalies has the opposite sign: a positive SST anomaly in the tropical Atlantic was associated with a negative NAO phase, while it is associated with a positive NAO phase in the simulations.

4. Atlantic SST anomaly impact on the Atlantic-European sector in the SINTEX coupled model

We have also investigated the influence of the Atlantic SST anomalies on the atmosphere in a simulation with the ECHAM4/OPA8 coupled model. During the SINTEX program, ECHAM4 was coupled in T30 resolution to OPA8, the oceanic GCM developed at LODYC in Paris (Madec *et al.*, 1999), with 31 vertical levels and a variable horizontal resolution of about 2°. As described in Guilyardi *et al.* (2003), the SINTEX model was integrated for 200 years, using the Levitus (1984) climatology for the ocean and a state of rest for the atmosphere as initial conditions. Sea ice was relaxed toward the observed monthly climatology. The simulation was fairly realistic at first, but it deteriorated progressively in the ocean because of a slow but continuous increase in salinity that was caused by inaccuracies in the freshwater budget at the air-sea interface. The main impact of the drift occurred at high latitudes where the salinity increase modified the water masses and deepened the wintertime mixed layer, resulting in a progressive extension of the regions of deep convection. While the Tropics are little affected, these artificial changes dominate the low-frequency variability in the high latitude oceans. Our analysis focused on the Atlantic sector during years 61 to 110, when the coupled model has reached an approximate statistically steady state and the oceanic conditions have not been much affected by the considerable drift of the simulation, but SST was not considered north of 58°N. As before, a third-order polynomial was subtracted from each variable at each grid point in order to remove the trends and low frequencies.

On the monthly to seasonal time scales, the air-sea interactions in the coupled model are rather realistic. As in the observations, the surface heat exchanges contribute both to generating SST anomalies and to damping them after they have been generated. As shown by Frankignoul *et al.* (2002), the net heat flux feedback is everywhere negative, generally ranging between 15 and 35 $W\,m^{-2}\,K^{-1}$, but it reaches up to 50 $W\,m^{-2}\,K^{-1}$ in the Tropics because the radiation feedback then also strongly contributes to the negative feedback. At extra-tropical latitudes, the negative heat flux feedback seems realistic, but it is much too strong in the tropical Atlantic. As a consequence, the tropical SST anomalies are too strongly damped, and they have a too large energetic impact on the atmosphere.

The influence of Atlantic SST anomalies on the atmosphere in the Atlantic-European sector was investigated using lagged MCA as in Section 2. Indeed, SST anomalies are primarily forced by the atmosphere in the coupled run, hence cause and effect need to be distinguished by lagging the oceanic and atmospheric fields. ECHAM4 in T30 resolution tends to overemphasize the ENSO teleconnection from the tropical Pacific, hence the ENSO signal was removed linearly from all monthly anomaly fields, to focus on Atlantic influence. A lagged MCA was performed both with monthly data as in Section 2, and by using seasonal anomalies for the atmosphere but monthly one for SST as in Rodwell and Folland (2002). It was done in various domains for SST (58°N-36°S, 58°N-25°S, 58°N-13°N, and 13°N-25°S) and the atmosphere (58°N-25°S, 58°N-13°N, 80°N-25°S, and 80°N-10°N). In all cases, the results were similar, showing statistically significant relations between SLP in summer and Atlantic SST anomalies one to three months before (statistical significance was estimated as before, using 100 Monte-Carlo permutations of the SLP maps). The relations between the two variables were strongest when using monthly data for both variables, and when SST was considered down to 25°S, although the co-variability was similar and

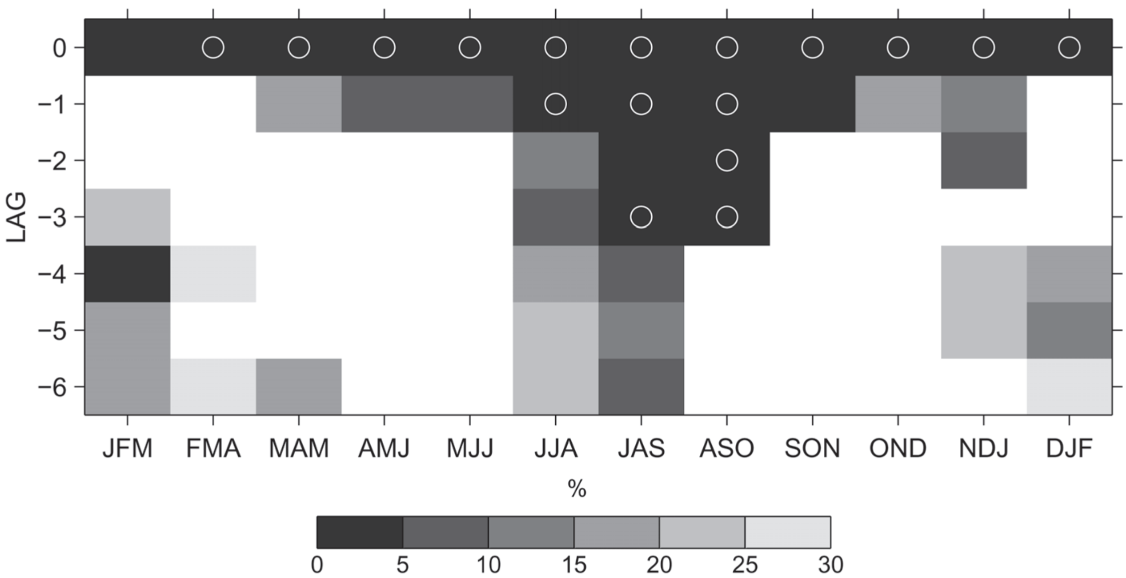

Fig. 7. Estimated significance level of the square covariance of the first MCA mode between monthly SLP and Atlantic SST anomalies in the ECHAM4/OPA8 simulation as a function of time lag (SST leads at negative lags), after linear ENSO removal. A circle indicates 0% significance level. The domain ranges from 58°N to 25°S (and from 100°W to 10°E for SLP).

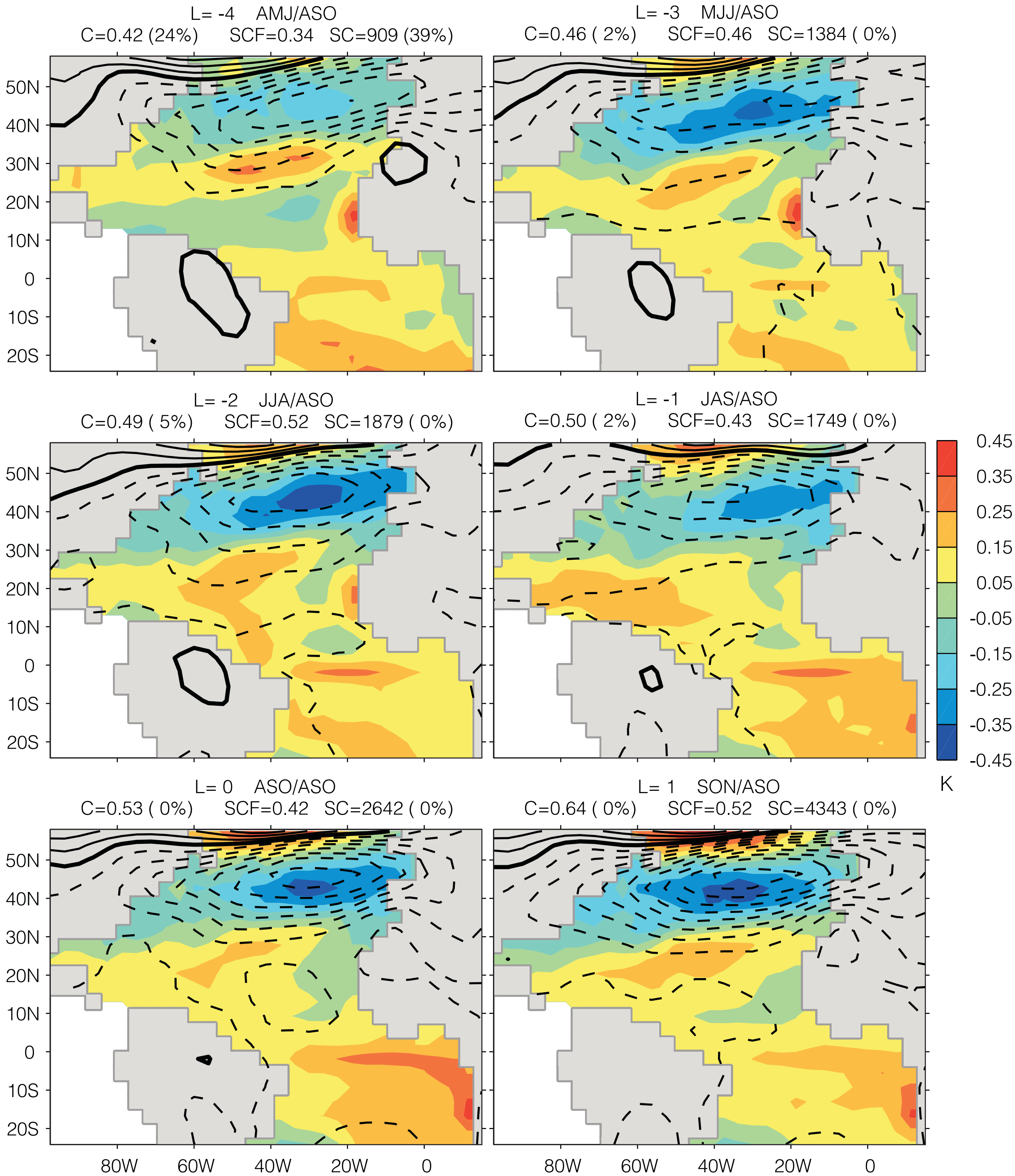

Fig. 8. Heterogeneous SLP covariance map in ASO (contour interval 20 Pa with negative values dashed) and homogeneous SST one (color) for the first MCA mode at various lags L in the ECHAM4/OPA8 simulation (SST leads at negative lag). The correlation r between the MCA time series, the SC fraction F, and the SC are indicated. The percentage in parentheses gives the estimated significance level.

still significant when limiting SST to 13N°-58°N, or 13°N-25°S. They were also much stronger with SLP than with Z500, which differs from the observations where the co-variability was better seen in mid-troposphere (Czaja and Frankignoul, 1999).

The MCA results are summarized in fig. 7 for the first mode between SLP and SST anomalies at lag 0 to –6 when both fields are considered between 25°S and 58°N. As lag 0 primarily reflects the forcing of the ocean by the atmosphere, the SST anomaly impact can only be recognized at negative lags. A significant co-variability when SST precedes is mainly found during summer. The maximum covariance patterns are illustrated in fig. 8 for SLP in ASO for lag 1 to –4 (results are similar in JAS and JJA). At lag 0 and 1, the patterns show that a NAO-like signal in the model generates a tripole SST anomaly in the North Atlantic (only part of the NAO northern pole can be seen because of the domain limit at 58°N), but note that both the SLP signal and the SST response are Pan-Atlantic ones extending to the South Atlantic. When SST precedes SLP by 1 to 3 months (negative lags), the first mode remains highly significant. There is little change in the maximum covariance patterns down to lag –4, although significance is then lost, presumably because the SST anomaly persistence is limited and the signal falls in the noise level. It is remarkable that the SST and SLP anomaly patterns in fig. 8 are very similar in lead and lag conditions, so that a positive air-sea feedback must be at play. The global correlation map in fig. 9 shows that the interaction mainly takes place over the whole Atlantic. The SLP signal has broad scales, resembling a NAO whose southern lobe extends southward to about 40°S between 90°W to the western part of the Indian Ocean. When the MCA is limited to a smaller domain, the regression patterns are little affected, so that their Pan-Atlantic character is not an artifact of the analysis. The MCA was also redone without removing ENSO, and it showed very similar results, even for the global correlation maps.

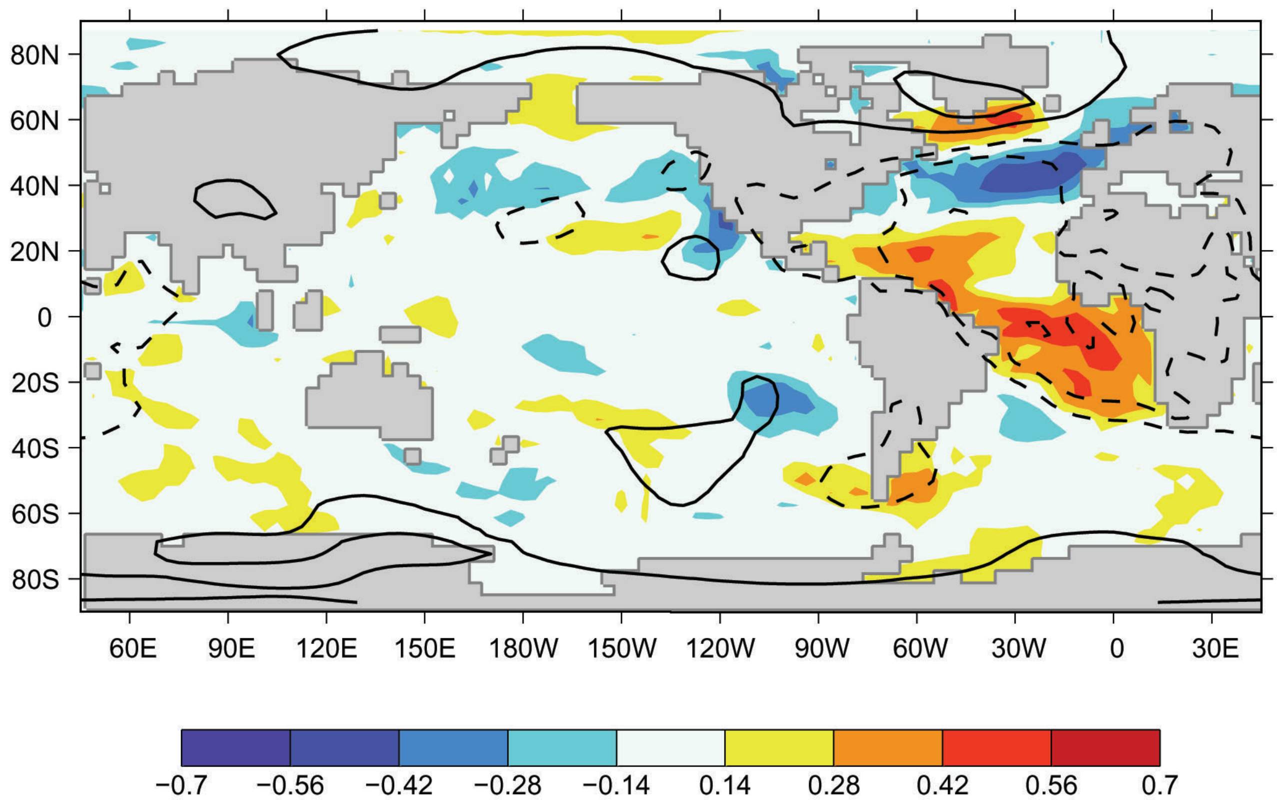

Fig. 9. Correlation of ASO SLP (contours) and JJA SST (color) with the SST anomaly time series at lag-2 in fig. 8. The SLP contours correspond to the color scale, with negative contours dashed.

The summer SLP signal is thus clearly forced by Pan-Atlantic SST anomalies, and to some extent it resembles that seen in the forced ECHAM4 simulations (fig. 5), except that the Indo-Pacific is not involved in the coupled run. Some hint of a SST influence on the NAO in early winter (NDJ) was also found, but for the second MCA mode. The results were slightly more significant when the MCA was performed without first removing ENSO, and regression analysis indeed showed a global pattern resembling that in fig. 4. The results are not shown, however, as they lacked robustness and were sensitive to the MCA domain.

5. Conclusions

SST anomalies in the North Atlantic have a significant influence on the observed atmospheric circulation in the European-Atlantic sector in early winter and in spring. The winter signal was discussed in CF, using the NCEP reanalysis. It describes a strengthening or weakening of the NAO, with the bulk of the SST anomaly impact coming from a horseshoe pattern in the North Atlantic. As discussed in the present paper, the spring signal is part of a global interaction primarily linking like-sign SST anomalies in the whole tropical band to changes in the Hadley circulation and in the atmospheric circulation over North America and the North Atlantic. The main SST influence seems to come from the northern tropical Atlantic, but the Indian and the tropical Pacific oceans are also involved, as well as the North Atlantic SST anomaly tripole. However, the influence of the latter is less significant in the NCEP reanalysis than in the NMC-NCAR archives (Czaja and Frankignoul, 1999), suggesting that the signal mainly originates from the Tropics.

The ensemble of 6 simulations with ECHAM4 in T42 resolution forced by the observed distribution of SST and sea ice anomalies during 1951-1994 showed that the SLP in the Atlantic-European sector was influenced by SST anomalies from early spring to late summer. In spring, the SLP signal seems to combine the NAO, the PNA, and the Southern Oscillation, while the corresponding SST and Z500 anomalies closely resembles those seen in the observations. Statistical significance is lost when the ENSO teleconnections are (linearly) removed, suggesting that, at least in the model, SST anomalies in the tropical Pacific play the dominant role. In summer, the atmospheric signal is strongly reduced poleward of 40°, and the ENSO influence becomes smaller. A NAO-like SLP signal is also found in early winter, but it is less significant and linked to SST anomalies of a polarity opposite to that seen in the observations. We thus could not detect any well-separated forcing by extra-tropical North Atlantic SST anomalies, suggesting a too low sensitivity of the model to mid-latitude forcing.

ECHAM4 was also considered in the coupled mode in T30 resolution. In the Atlantic-European sector, a SST anomaly influence on the atmospheric circulation was only found in summer. The atmospheric pattern resembles a NAO whose southern lobe widely extends southward and westward. It is linked to an Atlantic SST anomaly monopole between about 30°S and 20°N, extending northward in a tripole-like manner. The signal has no counterpart in the observations, but it shows some similarity with the summer signal in the forced simulations, except that SST anomalies in the tropical Indo-Pacific are also involved in the latter. Although the differences may be due in part to the lower resolution of ECHAM4 in the coupled mode, it is likely that they primarily arise from differences in the dominant SST anomaly modes.

In summary, the observed influence of mid-latitude SST anomalies in the North Atlantic is not simulated by ECHAM4, where the dominant SST anomaly influence comes from the Tropics. The influence of the tropical Atlantic seems better represented, but somewhat overestimated in the model. This is consistent with its too strong negative heat flux feedback in the tropical Atlantic (Frankignoul *et al.*, 2002). Clearly, further progress will require substantial model improvement.

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