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The contribution of ocean dynamics on the variability of European winter temperatures in a long coupled model simulation

Sebastian Wagner, Stefanie Legutke, Eduardo Zorita

30 pages with 13 figures

Abstract

A large part of the interannual variability of the European winter air temperature is caused by anomalies of the atmospheric circulation and the associated advection of air masses. However, part of the temperature variability cannot be linearly explained by such processes. Here, a long control simulation with a coupled atmosphere-ocean climate model is analyzed with the goal of decomposing the European temperature anomalies in an atmospheric-circulation-dependent part and a residual. The thermohaline circulation, closely connected in the model to the intensity of the Gulf Stream, lags the evolution of the temperature residuals by several years and does not seem to exert any control on their evolution. The variability of the oceanic convection in the northern North Atlantic on the other hand correlates with the temperature residual evolution at lags close to zero. It is hypothesised that oceanic convection produces a sea-surface temperature fingerprint that leads to the European temperature residuals.

Der Einfluss der Ozeandynamik auf die Variabilität der europäischen Wintertemperaturen in einer langen gekoppelten Klimasimulation

Zusammenfassung

Ein großer Teil der Jahr-zu-Jahr-Variabilität der europäischen Wintertemperaturen wird durch Anomalien innerhalb der atmosphärischen Zirkulation und dem damit in Zusammenhang stehenden Luftmassentransport verursacht. Dennoch kann ein nicht unerheblicher Teil der Temperaturvariabilität nicht linear durch solche Prozesse erklärt werden. In der vorliegenden Arbeit wird eine lange Kontrollsimulation mit einem gekoppelten Klimamodell mit dem Ziel untersucht, die europäischen Wintertemperaturen in einen durch die atmosphärische Zirkulation verursachten Teil und ein dazugehöriges Residuum aufzuspalten. Die thermohaline Zirkulation, welche im Modell eng mit der Intensität des Golfstroms verbunden ist, folgt der residualen Temperaturentwicklung mit einigen Jahren Verzögerung und scheint keinen Einfluss auf deren Entwicklung zu nehmen. Die Variabilität der ozeanischen Konvektion im nördlichen Nordatlantik andererseits korreliert mit der residualen Temperaturentwicklung ohne nennenswerte Zeitverschiebung. Es wird angenommen, dass die ozeanische Konvektion einen Fingerabdruck in den Meeresoberflächentemperaturen verursacht, welcher die residuale europäische Temperaturentwicklung steuert.

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1 Introduction

Winter air temperature anomalies in the European-North Atlantic sector are known to be determined to a large extent by the advection of air-masses by the atmospheric circulation, especially by the North Atlantic Oscillation (NAO). The NAO represents the most important pattern of tropospheric circulation anomalies in the wintertime in the Northern Hemisphere and essentially describes the strength of zonal winds over the North Atlantic and Western Europe (Wanner 2001 and references therein). In Western Europe, stronger zonal winds of oceanic origin lead to milder air temperatures during wintertime . In Greenland, on the contrary, they lead to a pronounced advection of cold air masses from the Arctic, causing below-average air temperatures.

A series of previous studies have investigated this link, which has been used to understand the mechanisms of the interannual variability of winter air temperature in the North Atlantic-European sector. The strength of this connection has motivated strong efforts to assess the potential predictability of the atmospheric circulation anomalies, since this could potentially lead to seasonal prediction of European temperature. However, on the one hand, the atmospheric circulation shows a strong turbulent character, leading to the conclusion that the air-temperature anomalies that are linked to the atmospheric circulation anomalies will be also essentially unpredictable several months in advance (Johansson et al. 1998). This argument is supported by studies from Wunsch 1999 and Stephenson et al. 2000 concluding, that the spectra e.g. of the NAO is nearly white and thus improper for climate prediction. On the other hand, other studies have aimed at identifying the effect of the sea-surface temperature anomalies, mainly in the North Atlantic ocean, on the North Atlantic atmospheric circulation, and exploit this link to set-up prediction schemes on air-temperature (Sutton and Allen 1997; Rodwell et al. 1999; Latif et al. 2000). For instance, recent modeling studies have shown that the evolution of the North Atlantic meridional overturning circulation may exhibit some decadal predictability. This predictability may be monitored and diagnosed in the model through the sea-surface temperatures in the North Atlantic (Latif, 2003 unpublished). Other modeling studies have however concluded that the signal of sea-surface-temperature forcing on the atmospheric circulation is small also at decadal scales (Paeth et al., 2003)

The link between the NAO and European winter temperature has also been exploited to reconstruct the evolution of the intensity of the winter atmospheric zonal circulation in the North Atlantic-European sector in the last centuries. These studies are partly based on information derived from temperature-sensitive climate proxy records (Luterbacheretal. 2002; Cook et al. 2002; Glueck and Stockton 2001). The statistical methods linking the NAO and the proxy records are calibrated with observational records, and therefore mostly represent the interannual co-variability of these variables. The longer time series of proxy data are subsequently used to reconstruct past states of the NAO.

European winter temperatures, however, may be potentially affected by other factors than the variability of the atmospheric circulation alone. At centennial timescales variations of the external radiative forcing are the obvious candidate. The interpretation of temperature variability, caused by external forcing, as due to the atmospheric circulation anomalies may potentially lead to erroneous reconstructions of the NAO (Zorita and González-Rouco 2002). But other mechanisms internal to the climate system could also lead to misinterpretations.

At long timescales it has been argued that a collapse of the meridional overturning circulation in the North Atlantic could lead to cooling of the surrounding continental regions (Rahmstorf and Ganopolski 1999). Opposed to that, it has been common believe that the relatively mild winter temperatures in Europe compared to their counterparts in North America are caused by the heat transport due to the Gulf Stream and/or the North Atlantic Meridional Circulation. Recently, some model results indicate that this zonal temperature gradient may be caused by the mean atmospheric circulation (Seager et al. 2003), although it is not clear if this conclusion also applies to the interannual or decadal variability of European winter temperatures.

A possible candidate to explain part of the temperature variability that is not directly liked to the atmospheric circulation is the ocean dynamics. In this paper we have tried to gain insight into the part of the European winter temperature anomalies that are, in a statistical sense, independent of the atmospheric circulation anomalies. The motivation for this analysis is twofold: First, to ascertain to what extent the paleoclimatic reconstructions of the atmospheric circulation based on European proxy data may be potentially contaminated by other physical processes that may give rise to variability in the temperature record. Second, to assess if these processes may have a potential predictability longer than the several days typical of the atmospheric circulation. If this is the case, long-range prediction schemes could be set-up at least for this part of the temperature variability. Numerous model studies have been aimed at identifying physical mechanisms responsible for the quasi-oscillatory behavior of the climate in the North Atlantic. These mechanisms may depend on the model used. For instance, in models where the atmospheric circulation is sensitive to sea-surface temperature anomalies, these mechanisms can be described as a coupled ocean-atmosphere variability mode (Latif and Barnett 1994; Timmermann et al. 1996; Latif 1998; Zorita and Frankignoul 1997). In models where the reaction of the large-scale atmospheric circulation is weak, modes where only the ocean plays a leading role have been identified, perhaps excited by white local stochastic forcing by the atmosphere (Delworth et al. 1993; Delworth and Greatbach 2000). Although this topic is certainly of ultimate relevance for the understanding of European temperature anomalies, we restrict ourselves in this work to analyse the immediate cause of European temperature anomalies that are not directly related to atmospheric circulation anomalies, and not on the possible existence of variability modes in the model in the present study. However, if in reality coupled ocean-atmosphere modes exist over the North Atlantic, the ultimate physical cause cannot be disentangled.

For our purpose, the observational record is too short. Hence we analyze a long integration (1000 years) performed with the state-of-the-art coupled ocean-atmosphere climate model ECHO-G. The spatial coverage of simulated data allows for a more comprehensive analysis of the statistical links than the available observations, and the length of this simulations potentially provides for more reliable statistical signals. Admittedly a coupled climate model does not represent the whole variety of the real climate, and thus the results of this study can only be interpreted as a guidance for possible similar applications with observational data.

The paper is organized as follows. In section 2 the coupled model and the simulation are briefly introduced. In section 3, the statistical analysis to filter out the contribution of the atmospheric circulation anomalies to air-temperature variations is presented and the resulting time series of average winter temperature are briefly statistically analyzed. In section 4 several climate fields from the simulation are considered to formulate causal mechanisms for the temperature variability. The paper is closed with the conclusions in section 5.

2 Model description and simulation

The global climate model consists of the spectral atmospheric model ECHAM4 (Roeckner et al., 1996) and the ocean model HOPE-G (Wolf et al., 1997), both developed at the Max-Planck-Institute of Meteorology in Hamburg. In this simulation the model ECHAM4 has a horizontal resolution of T30 (approx. 3,75° x 3,75°) and 19 vertical levels, five of them located above 200 mb. The horizontal resolution of the ocean model HOPE-G is about 2.8° x 2.8° with a grid refinement in the tropical regions, where the meridional grid-point separation decreases progressively to the equator, reaching a value of 0.5°. This increased resolution allows for instance for a more realistic representation of ENSO events. The ocean model has 20 vertical levels.

To avoid climate drift in such a long simulation, additional fluxes of heat and freshwater are applied to the ocean. These fluxes were diagnosed in a coupled spin-up integration with restoring terms that drive the sea-surface-temperature and sea-surface salinity to their climatological observed values. This flux adjustment is constant in time and their global integral vanishes.

In this simulation the external forcing was kept constant in time and set to the values of the present climate. The model was integrated for 1000 years.

3 European winter air temperature decomposition

The time series of the winter (December-February, DJF) near-surface air temperature average in the geographical window (0° , 30° E, 45° N, 70° N), together with the Northern Hemisphere average DJF temperature, is shown in Figure 1. The correlation between both time series is 0.31 at interannual time scales and 0.58 at timescales longer than 10 years. The European temperature (ET) time series is strongly related to the North Atlantic Oscillation, as it is illustrated in Figure 2, showing the local correlation pattern between ET and the simultaneous sea-level-pressure field in the North Atlantic-European sector over the whole integration period. This result correspond quite well with similar analysis with observational data (Hastenrath and Greischar, 2001). Actually, the correlation between ET and the NAO index, calculated as the leading Empirical orthogonal Function (EOF) of the SLP in the North Atlantic reaches 0.51 in the model. To estimate the amount of variability in ET that can be explained by the atmospheric circulation alone, a simple linear regression model between ET and the time series of the 10 leading EOFs

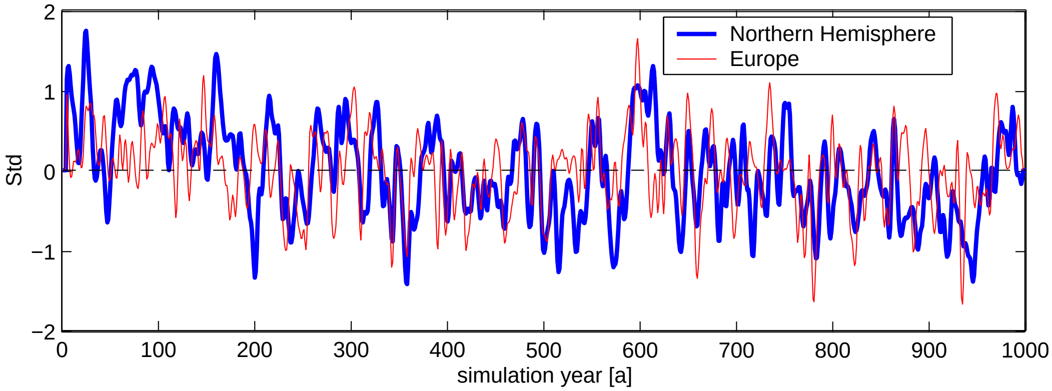

Figure 1: Simulated Northern Hemisphere and European standardized near-surface winter air temperatures (10 years Gaussian filter).

of the SLP field has been set up and fitted in the whole simulation.

$$ET(t) = \sum_{n=1}^{10} a_k pc_k(t) + ETR(t) \tag{1}$$

where $pc_k(t)$ are the time series of the k$^{\text{th}}$ EOF, a_k are the regression coefficients and ETR are the European temperature residuals that cannot be linearly described by the leading SLP EOFs. The time series ETR(t) is the focus of this analysis. At a first sight a shortcoming of this approach is that apriori the atmospheric and oceanic parts possibly influencing the European

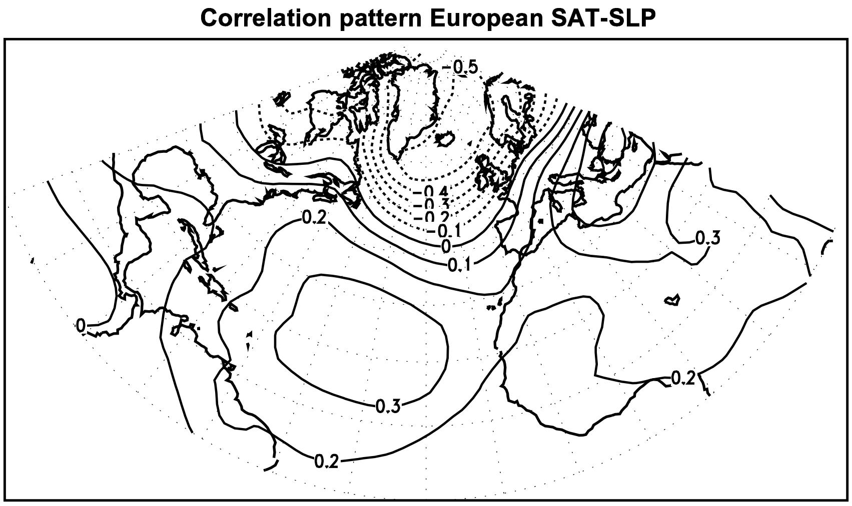

Figure 2: Correlation pattern between the European near-surface winter temperatures (SAT) and the SLP field in the North Atlantic. The pattern in general shows the fingerprint of the NAO.

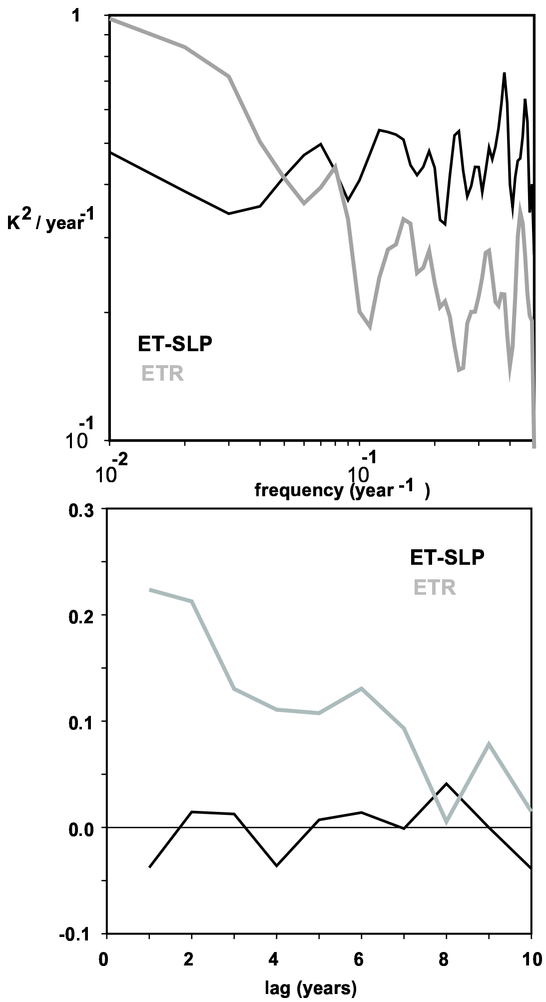

Figure 3: Spectra and autocorrelation function of the atmospheric related (SLP-ET) and the residual related (ETR) component of the winter European near-surface air temperature. Note the increased power of the ETR-component at low frequencies.

winter temperatures are separated, whereas numerous studies point to the existence of a coupled air-sea-mode within the North Atlantic (Timmermann et al. (1996), Sutton and Allen (2000)). In terms of the above introduced regression model this would imply an influence of the ETR on the SLP-PCs and vice versa. However, since ET contains temperature over land areas, the causal influence of ET on SLP anomalies will be generally small. At interanual time scales the total variability of ET is decomposed in 60 % that can be described by the SLP EOFs (the first term on the r.h.s. in Eq. (1)) and 40 % of the variance ascribed to ETR. Therefore, there exists a substantial amount of temperature interannual variance that is still linearly independent of the atmospheric circulation as represented by the SLP field. At longer time scales the amount of variance described by ETR increases. For example, at timescales longer than 10 years the ET variance is decomposed in 35 % for the SLP-dependent part (hereafter SLP-ET) and 55 % for ETR. Hence, at these timescales the SLP-independent contribution to ET is dominant. This is illustrated in Figure 3, that shows the autocorrelation function and the spectra of SLP-ET and ETR. This figure shows that the timescales at which the SLP fingerprint on temperature becomes weaker than ETR is about 15 years. The spectrum of SLP-ET is essentially white, reflecting the atmospheric forcing of this temperature component. The spectrum of ETR is white from high frequencies up to about periods of 10 years and exhibits a weak peak at periods of about 12 years. The persistence of ETR is longer than that of SLP-ET, which exhibits virtually no persistence, although the interannual autocorrelation of ETR does not attain very high values. The variability of ETR will not be completely due to a single factor. For instance, all noise that is not connected to the SLP variability is also contained in ETR. However, several features indicate that ETR is associated to real physical mechanisms that act on longer scales. The correlation of ETR with the Northern Hemisphere average temperature is larger than in the case of SLP-ET: 0.40 at interannual timescales and 0.65 and timescales longer than 10 years. To gain insight into the nature of these processes the associated correlation patterns between ETR and the North Hemisphere temperature, sea-surface-temperature (SST) and SLP are shown in Figure 4.

For comparison purposes the same correlation patterns are shown for the circulation dependent component SLP-ET. The temperature regression patterns associated with SLP-ET and ETR show clear differences, whereas the temperature linked to SLP-ET shows the well-known fingerprint of the North Atlantic Oscillation, with warmer than normal temperatures in Western Europe and colder than normal in Greenland (known as ”Greenland below” in NAO terminology). The temperature associated with ETR shows the same sign over Northwestern Europe and the North Atlantic ocean, with negligible anomalies elsewhere. The amount of temperature variance described by these two patterns is 12 % and 8 %, respectively, although they are not orthogonal to each other and, therefore, some part of the described variance is common to both. For SST similar results are obtained. The pattern related to SLP-ET shows the tripo-

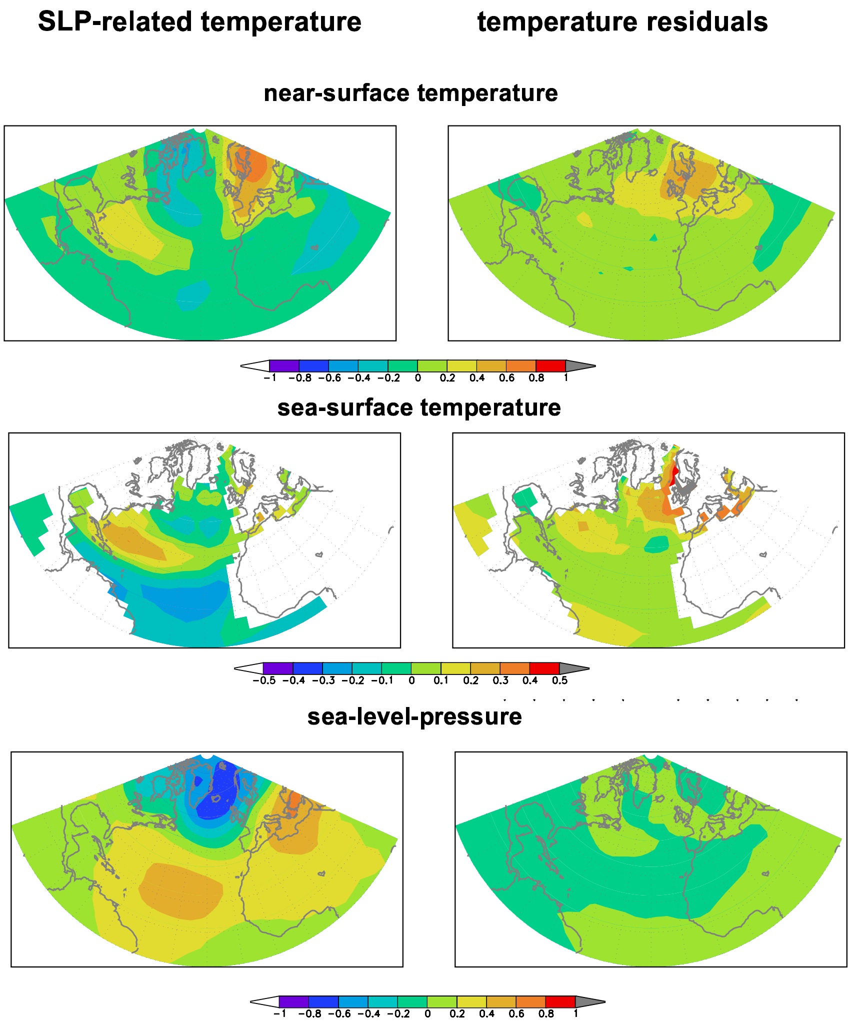

Figure 4: Local correlation patterns between both components of ET, SLP-ET and ETR, and near-surface air temperatures (SAT), SST and SLP fields in the North Atlantic sector. Note the positive correlation within the SAT and SST-temperature residual patterns within the Northeast Atlantic, which is unrelated to the SLP.

lar pattern of SST anomalies, which is also found in similar analysis with observational data (Cayan 1992). The ETR-associated pattern is concentrated on the Western European coasts and shows the same sign over the North Atlantic and the Mediterranean. Finally, the SLP fingerprint reflects the way in which both temperature components have been statistically defined. The pattern linked to SLP-ET shows the meridional pressure dipole typical of the positive phase of the NAO, and the ETR-component is virtually uncorrelated with the SLP field. The ETR component is also lag-correlated with the air temperature (SAT), SST and SLP fields, contrary to the

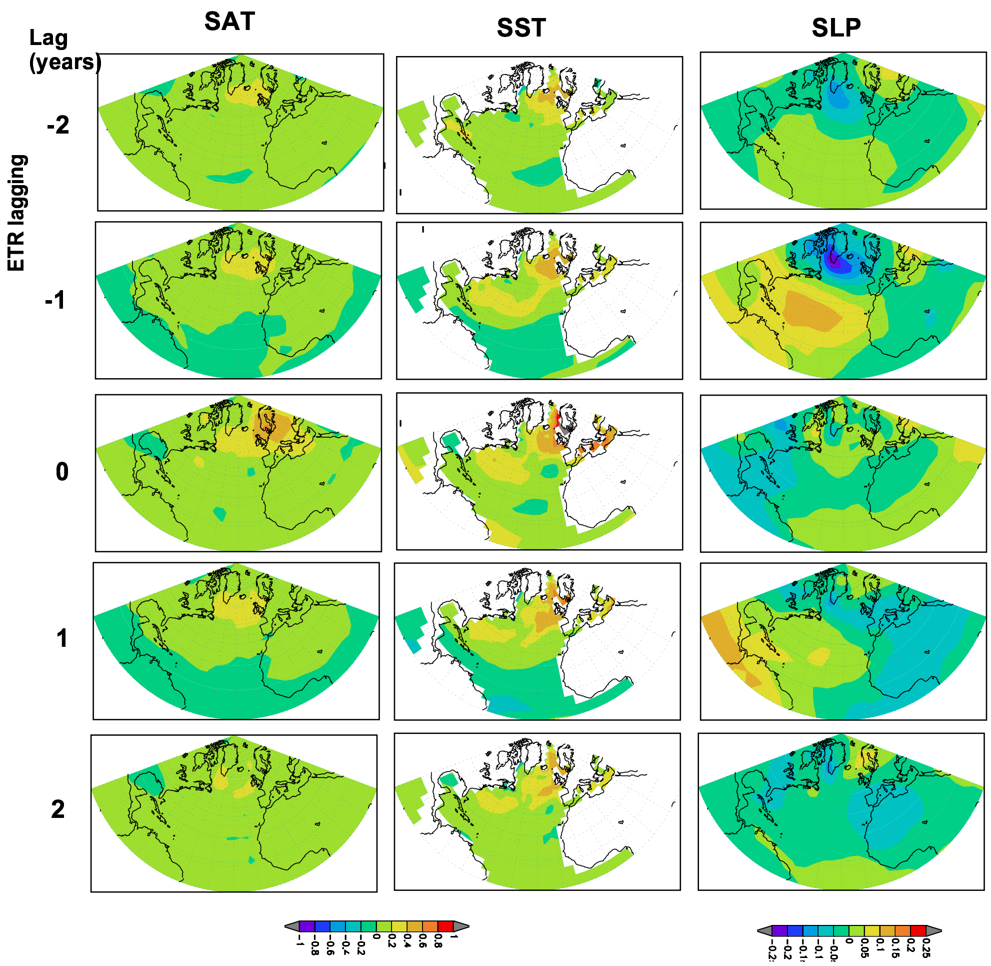

Figure 5: Lag-correlation patterns between the temperature residuals ETR and the air temperature, SLP and SST fields in the North Atlantic. Note the emerging SAT- and SST-anomaly pattern around Iceland several years in advance.

SLP-ET component, which shows no correlation with these fields when a lag is introduced. In Figure 5 the lag-correlation between the ETR component and those fields is shown. The signal associated with ETR emerges about 2 years in advance in the region around Iceland and expands subsequently into the whole North Atlantic, thereby growing in amplitude. This amplitude reaches its maximum at lag zero for SAT and SST. The SLP signals at non-zero lags is weak, but still discernible. By construction, the correlation between SLP and ETR is negligible at zero lag. The evolution of the signals at different lags suggest already a possible mechanisms for the emergence of the ETR temperature anomalies, namely, the oceanic convection at high

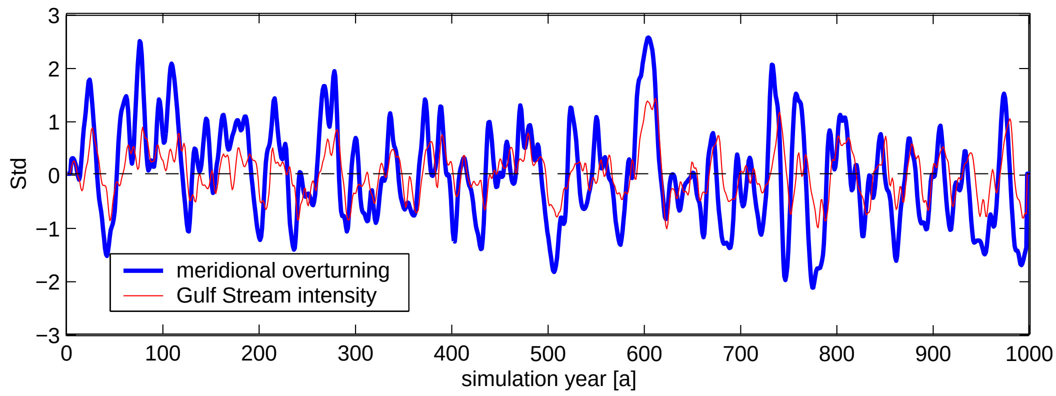

Figure 6: Standardized time series of the Gulf Stream and meridional overturning intensities in the North Atlantic (10 years Gaussian filter). For definitions of these indices, see text. Note the strong connection between the horizontal (Gulf Stream) and vertical (overturning) oceanic circulation.

latitudes in the North Atlantic. However, also other mechanisms, which are also partially connected to oceanic convection, such as the intensity of the Gulf Stream or the oceanic meridional overturning in the North Atlantic, will be analysed.

4 Relationships of temperature residuals (ETR) to ocean dynamics

The time series of the intensity of the Gulf Stream and of the North Atlantic meridional overturning are shown in Figure 6. The intensity of the Gulf Stream (GS) for each year has been defined here as the amplitude of the pattern of the long-term mean stream function at 100 m depth. It is calculated as the projection of the mean stream function onto the stream function anomalies for a particular year. The meridional overturning index (OT) has been defined as the maximum of the meridional mass-transport stream function in the North Atlantic. Both time series, GS and OT, are correlated to each other with a correlation of 0.47 at interannual time scales and 0.73 at timescales longer than 10 years. Highest interannual correlations of 0.57 are reached when OT is leading by 2 years. Therefore, both ocean dynamics, horizontal circulation and meridional circulation are closely related to each other in the model.

Both are also statistically related to the ETR time series, as shown in Figure 7, which depicts the lag-correlation function between ETR, and GS and OT, respectively. The temperature resid-

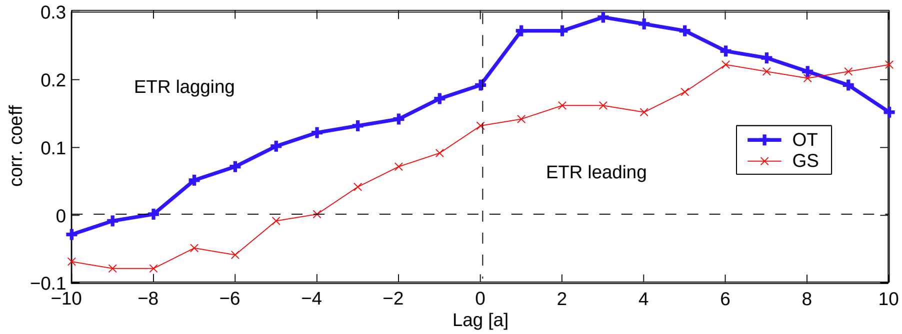

Figure 7: Lag-correlation between the ETR time series and the intensities of the Gulf Stream (GS) and of the North Atlantic meridional overturning (OT). Note the lagged response of GS and OT on ETR.

uals ETR lead, somewhat surprisingly, the evolution of OT by about 2-3 years. The lag between ETR and GS is even longer, with ETR leading around 6 years. This might be due to the remote location of the maximum values of the stream function off the coast of Florida. Therefore, although the Gulf Stream and the meridional overturning may contribute to the intensity of ETR, they do not seem to be the ultimate cause for the variations of the temperature residuals. A clearer picture of the physical mechanisms giving rise to ETR is found by looking at oceanic convection at high latitudes in the North Atlantic. In this climate model, the average locations where oceanic convection takes place are somewhat unrealistic. In Figure 8a the mean potential energy liberated in convective processes is shown. Most convective activity occurs, on average, south of Iceland and to a lesser extent in the Barents Sea.

However, oceanic convection within the North Atlantic in reality takes mainly place in the Labrador Seas (Labsea Group 1998). A second region where convective processes in the Northern North Atlantic occur is located within the Irminger sea on the eastern coast of Greenland (Pickart et al. 2003). In the model convection south of Iceland is quite constant in time and most of the variations of the convective activity occur South of Greenland, as shown in Figure 8b, which depicts the interannual standard deviation of the potential energy released by convection. The convective activity south of Greenland is closely connected to the temperature residuals ETR, as illustrated in Figure 9a. The possible causal relationships between convective activity south of Greenland and ETR is supported by the lag correlation function between the convection and ETR, shown in Fig. 9b, also noticeable in the time series themselves, even when they are smoothed by a 10-years Gaussian low pass filter (Fig9a). Convective activity South of

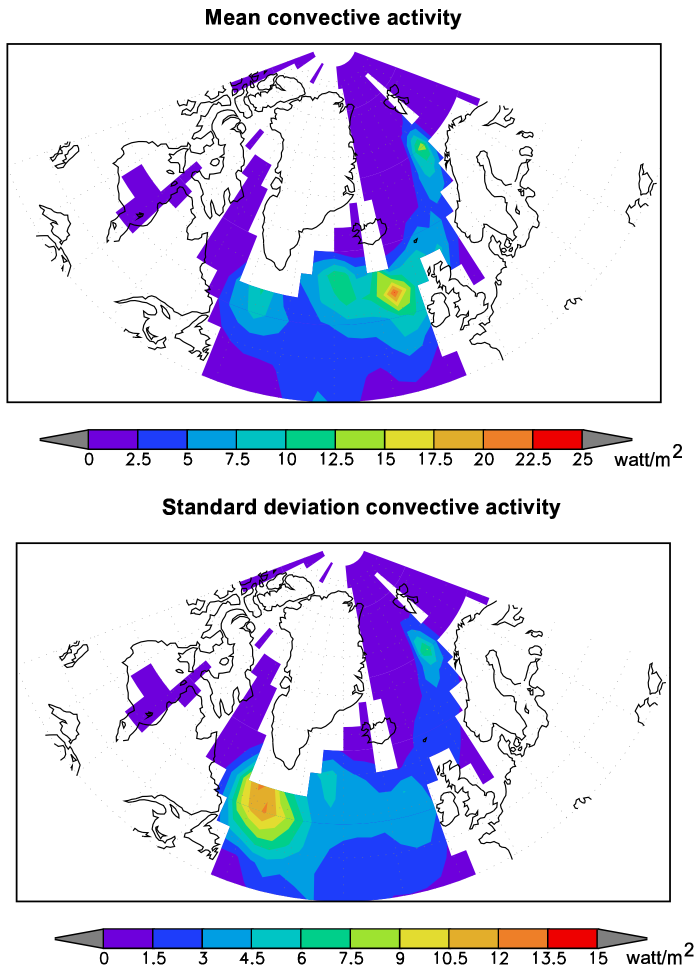

Figure 8: Long-term mean and standard deviation of the potential energy released by oceanic convection. The region of highest convective variability is located south of Greenland.

Greenland seems to modulate the intensity of the Gulf Stream and of the meridional overturning, with several years lag. Figure 9b also shows the lag-correlation function of the convective activity on one side, and GS and OT on the other side (the corresponding correlations for the SLP-dependent part SLP-ET are negligible). The meridional overturning seems to react more swiftly to variations of the convective activity, with a lag of about 3–4 years. The correlation at interannual time scales is also high, with a maximum of almost 0.6. The reaction of the Gulf Stream is not that clearly discernible, possibly due to the already mentioned remoteness of the center of action. The reaction of GS seems to be more sluggish, with a lag of about 6 years, and the correlation tends to be also lower, with maximum values of 0.4. Probably,

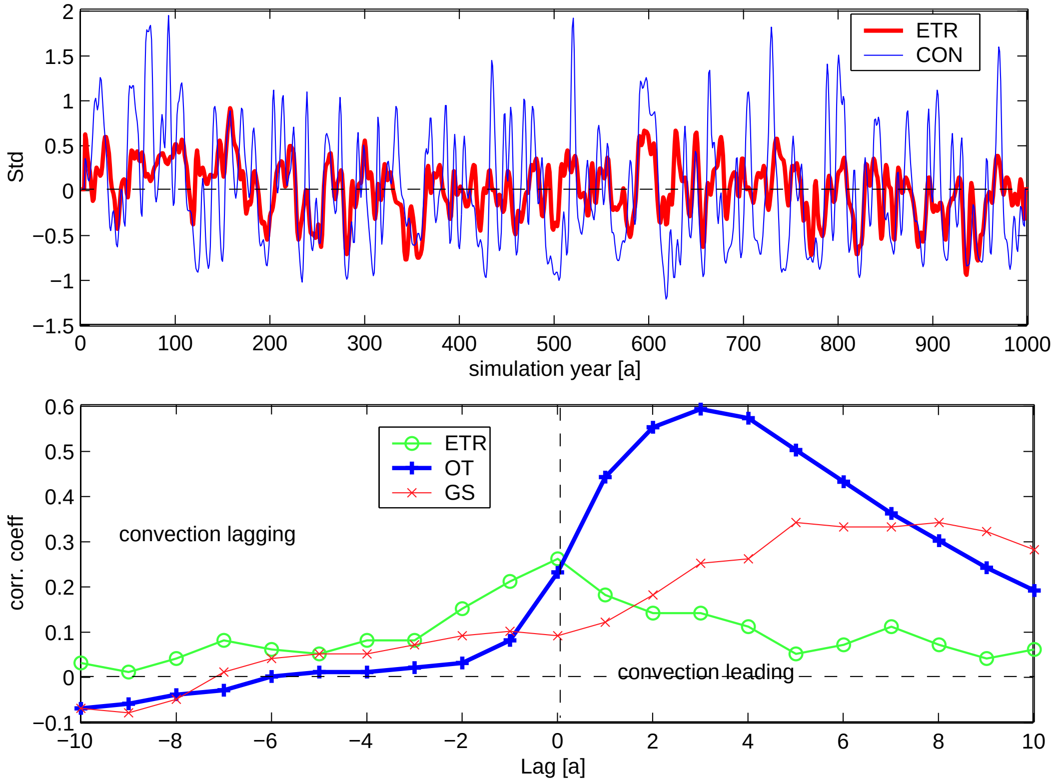

Figure 9: a): Standardized time series of the temperature residuals ETR and oceanic convective activity (10 years Gaussian filter);b) Lag-correlation between oceanic convection and the residuals ETR, the Gulf Stream intensity and the meridional overturning. Note the lag-0 correlation between convection south of Greenland and ETR.

also other factors contribute to the variations of GS, such as wind-stress, so that convection feeds only partially to the intensity of the subtropical Gulf Stream. The intensity of the Gulf Stream is affected by the baroclinic Rossby waves that need several years to cross the North Atlantic basin. Recent ocean-model studies driven by observed surface fluxes have indicated a lag of about 7 years between surface heat forcing and meridional heat transport (Gulev et al. 2003). The temperature residuals react with a zero lag to variations in convection, but with quite weak correlations around 0.25. In order to proof the robustness of the convection-ETR relationship a cross-spectrum analysis (v. Storch and Zwiers 2000) has been performed. This analysis gives information about the convection-ETR relationship in the frequency domain, that means at which frequencies the time series are interrelated to a certain extent.

Fig. 10 shows the coherency-spectrum together with the 90% level of significance. It clearly shows that in general the relationship is stronger at lower frequencies which supports the long term memory of ETR.

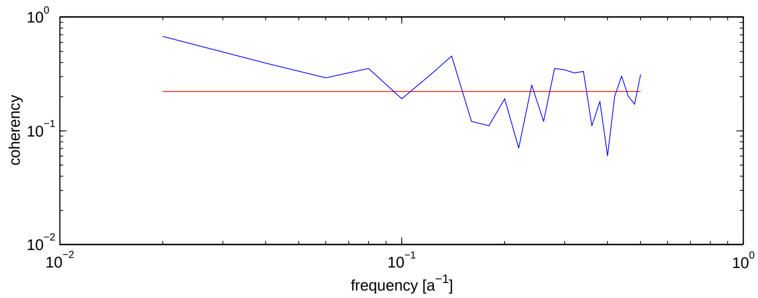

Figure 10: Coherency spectrum of Cross spectrum analysis between convection south of Greenland and ETR. The red line indicates the 90 % level of significance. Note the increased co-variability between ETR and convection at low frequencies.

The instrumental of oceanic convection anomalies in producing anomalous air-temperature anomalies at timescales somewhat longer than interannual is illustrated in Fig. 11.

The correlation between averaged convective activity and SAT shows a temperature pattern that grows in time and expands in the North Atlantic basin. Temperature anomalies reach their maximum amplitudes and extension with a few years lag after convection. At lag 3 the correlation between convection and surface heat flux (Fig.12) indicates that heat is lost by the ocean south of Greenland, in the areas where convection has strong variability in the model, and that surface heat flux is directed downward in the Western Atlantic basin. The overall effect is transport of heat from the convective active sites westward, probably carried by the mean atmospheric circulation.

5 Forecast exercise

The lag correlations between the temperature residuals and some oceanic fields in the North Atlantic, shown in Fig. 5, suggest the possibility of designing a statistical prediction scheme, at least for ETR. In this section we try to explore the order of magnitude of the predictability of the ETR time series in the world simulated by the climate model, without loosing sight of possible applications in the real world. The results from the climate model simulation will surely represent an upper performance limit to a similar scheme based on real data. In practice the oceanic field that could be more reliably measured will be the SST field. Other oceanic fields, such as convection, or meridional overturning would not be available in a real prediction

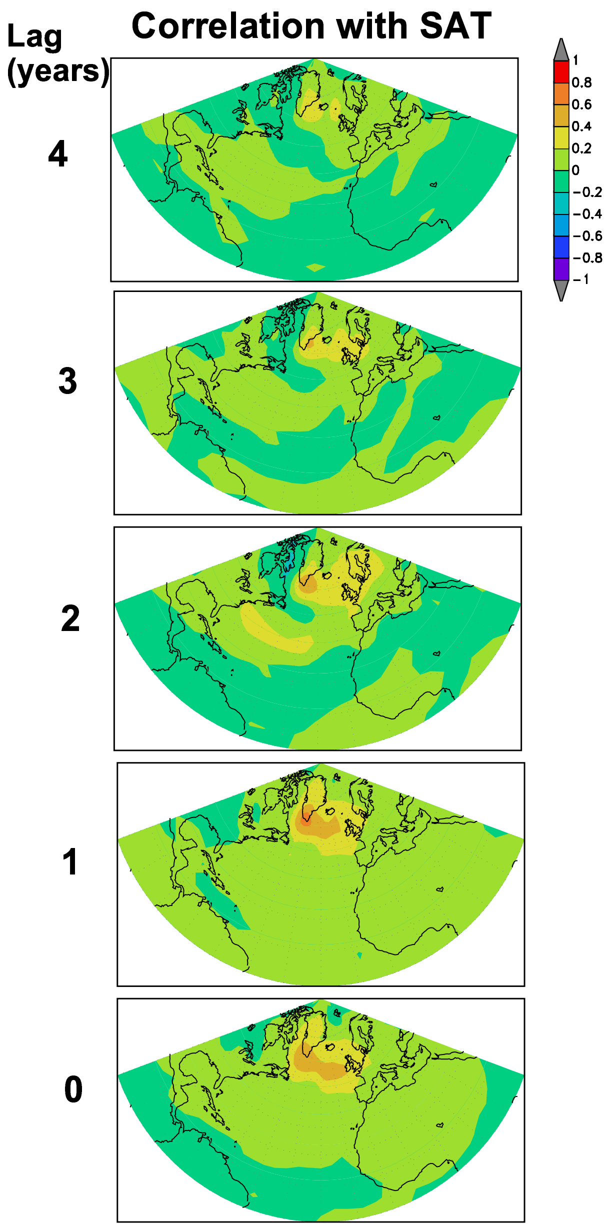

Figure 11: Lag-correlation pattern between the averaged oceanic convection at high latitudes in the North Atlantic and the SAT field. Note the fast response of SAT on convection opposed to the Gulf Stream and the overturing circulation (Fig.9b).

scheme. Therefore , only the SSTs will be used here. The prediction scheme suggested here for ETR based on the SST simulated the previous years is a linear regression model between the SST anomalies and the ETR. The estimation of ETR(t) could be set up as a regression equation

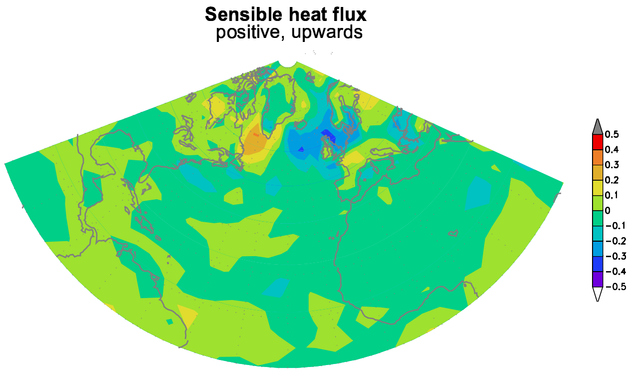

Figure 12: Lag-correlation patterns between the temperature residuals ETR and sensible heat-flux in the North Atlantic. Note the increased heat flux from the ocean to the atmosphere south of Greenland

between the SST anomalies at years $t-\tau,..,t-1$ and the ETR at time t:

$$\hat{E}TR(t) = \sum_{i=1}^{N}\sum_{k=1}^{\tau} sst(i,t-k)p(i,k) + \epsilon(t) \quad (2)$$

where i represents the grid point and k the time lag, and ϵ are the residuals that cannot be described by the regression model and p are the regression coefficients.

To avoid a huge number of predictors $sst(i,t-k)$, the regression model can be formulated in terms of the Extended Empirical Orthogonal Functions (EEOF, Weare and Nasstrom 1982) of the SST field . The EEOF method is an extension of the classical EOF analysis in which the original field is augmented by an additional time dimension:

$$asst(i,k,t) = sst(i,t-k) \qquad k = 0, m-1 \quad (3)$$

where i is the grid point index and k represents the additional (time) dimension. Usually m is of the order of just a few time lags.

Therefore, EEOF identifies the most important, in terms of described variance, sequences of patterns in a given field. After performing an EEOF analysis of the North Atlantic SST data, the leading 10 EEOFs are retained, and the corresponding principal components enter into equation 2 as predictors. In this exercise a time window of m=5 years has been used to compute the EEOF, in accordance with the expected maximum lag between ETR and the SST field found in the previous calculations.

The regression model can therefore be rewritten as:

$$\hat{T}(t) = \sum_{l=1}^{M} q_l epc_l(t) + \epsilon(t) \tag{4}$$

where q_i are the regression coefficients, epc_i are the principal components of the EEOF. Note that in eq. 4 epc_i(t) contains information from the SST field at time t and at $t-1, t-2, t-3, t-4$, since they are the result of projection the EEOF patterns onto the augmented field:

$$epc_l(t) = \sum_{k=0}^{4} \sum_{i=1}^{N} sst(i, t-k) eeof(i, k) \tag{5}$$

To calibrate the prediction scheme, only data from the first 500 years of the simulation have been used in all steps: calculation of the EEOF, calculation of their principal components $epc(t)$, and estimation of the regression coefficients q_l.

The model is then validated in the last 500 years of the simulation. To keep this prediction exercise realistic, the estimation of the predicted ETR at time t should not use any information of the SST field available at time t, but only information available in previous times. This is achieved by eliminating the term $k = 0$ in the right-hand-side of eq. 5:

$$e\hat{p}c_l(t) = \sum_{k=1}^{4} \sum_{i=1}^{N} sst(i, t-k) eeof(i, k) \tag{6}$$

Therefore, the EEOF patterns are truncated in the time dimension to exclude information from simultaneous time. Formally this truncation is also common in applications of classical EOF analysis. For instance, EOF patterns may have been calculated in a certain calibration period and the associated principal components are estimated in another period, when observations may be more sparse: the grid-points corresponding to missing values are then excluded from the calculation of the associated principal component.

The final estimation of ETR(t) is then carried out by inserting the estimated values $e\hat{p}c_l(t)$ into equation 4. The results of this prediction exercise is illustrated in Figure 13a, where the simulated and estimated ETR(t) in the validation period are shown. The correlation between both is 0.38 at interannual timescales and 0.58 at timescales longer than 5 years. The correlation is admittedly low, specially at interannual timescales, but considering that the prediction scheme uses only information available in the previous winter, it may be encouraging. This correlation is also higher than the autocorrelation at lag 1 of the ETR time series, which is 0.23.

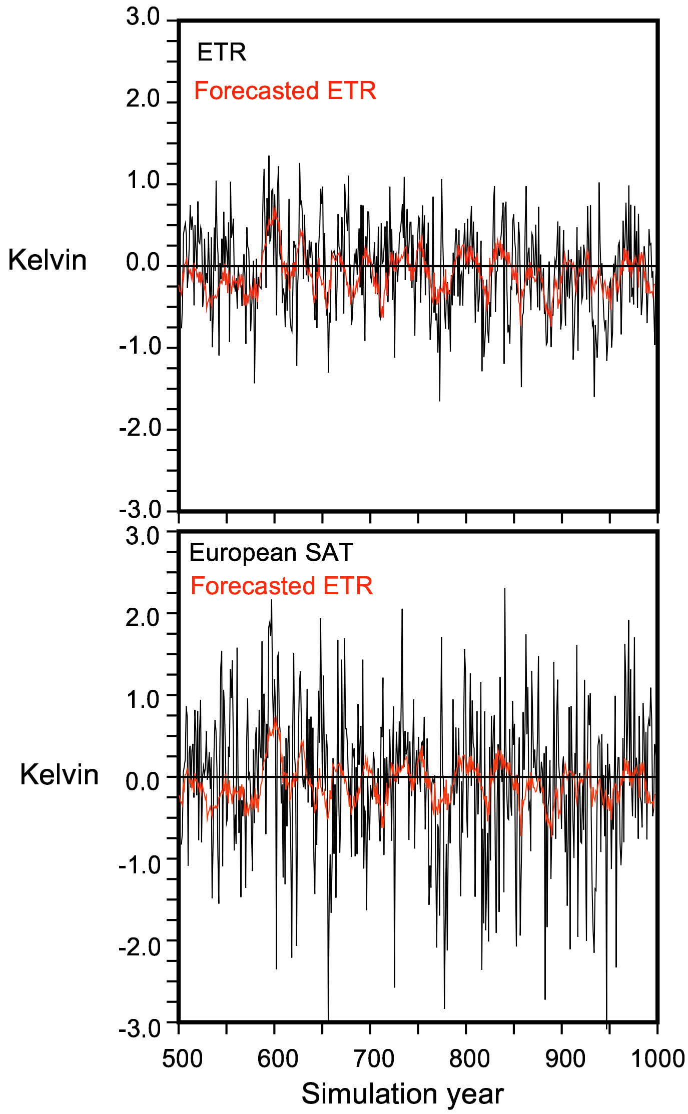

Figure 13: Statistically forecasted time series of the temperature residuals ETR compared to the simulated ETR and to the complete European SAT. Note the resemblance of the low-frequency variability between the simulated and the forecasted temperatures in both panels.

Therefore, the present prediction scheme also yields better results than simple persistence. The comparison between the estimation $E\hat{T}R$ and the average European temperature, i.e ETR plus the SLP-dependent part, is of course more unfavorable (Fig 13b), the correlation being 0.24 at interannual time scales and 0.44 at timescales longer than 5 years. The reduction in correlation is almost as large as it could be expected from the increase in variance stemming from the SLP field, unrelated to the predictor field.

6 Concluding remarks

In this climate simulation with the climate model ECHO-G the amount of variance of European winter air temperature that is related to the SLP field is about half of the total variance at decadal timescales. The origin of most of this variability seems to be related to the convective activity in the North Atlantic ocean. Since the observational record is too sparse and too short to ascertain if this is also the case in the real world, simulations with other models should be analyzed.

If these results can be translated to the real world, some consequences could be derived pertaining paleoclimatic reconstructions and long-term climate prediction. Concerning the latter, temperature proxies are often used as indicators of past atmospheric circulation anomalies, due to the, at interannual timescales, strong connection between European winter temperatures and the North Atlantic Oscillation. This relationship may weaken at longer timescales due to the effect of other external factors influencing temperature, such as variations in external radiative forcing. If the model results presented here can be applied to the real world, the contribution to air temperature in continental areas may be affected at decadal time scales by other internal factors of the climate systems, that are not directly connected to the atmospheric circulation. The interpretation of the proxy signal as being completely caused by atmospheric circulation anomalies may potentially lead to reconstructions with a non-negligible error (see Fig. 4). The associated temperature anomaly patterns over continental areas are difficult to differentiate from each other, and only the temperature see-saw between Europe and Greenland would imply a clear temperature fingerprint of the direct influence of SLP.

The origin of oceanic convection anomalies, that in turn modulate a part of the European temperature, has not been the focus of this study. Numerous modelling and observational studies link decadal variations of the thermohaline circulation and oceanic convection in the North Atlantic at high latitudes to one or several physical mechanisms: a coupled atmosphere-ocean mode, an ocean-alone or be just a oceanic response to atmospheric forcing. These mechanisms may involve sea-ice export from the Arctic Ocean (Lohmann and Gerdes 1998; Holland et al. 2001), fresh water fluxes (Mysak 1990), heat fluxes associated to atmospheric circulation anomalies (Eden and Jung 2001), or water density anomalies advected by ocean currents (Delworth et al. 1993; Häkinnen 2000). The spectrum of ETR (see Fig. 3) shows a peak at about 12 years that might be an indication of the existence of a quasi-oscillatory mode. Although the time series of the temperature residuals ETR has been constructed so that it contains no information of the simultaneous SLP field, it cannot be ruled out that lagged relationships between large-scale atmospheric forcing and the oceanic circulation my be involved in the generation of the convection anomalies. (Pickart et al. 2003). For the purpose of this model study, however, it was shown that on decadal and secular timescales the low frequency oceanic variability may act as a pacemaker, possibly pre-conditioning the long term European winter temperature anomalies.

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