# Predictability of the North Atlantic Thermohaline Circulation

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## Abstract

Sea surface temperature (SST) observations in the North Atlantic indicate the existence of strong multi-decadal variability with unique spatial structure. It is shown by means of a new global climate model which does not employ flux adjustments that the multi-decadal SST variability is closely related to variations in the North Atlantic thermohaline circulation (THC). The close correspondence between the North Atlantic SST and THC variabilities allows in conjunction with the dynamical inertia of the THC for the prediction of the slowly varying component of the North Atlantic climate system. This is shown by classical predictability experiments and greenhouse warming simulations with the global climate model.

## 1 Introduction

The North Atlantic thermohaline circulation is an important component of the global climate system. Strong and rapid changes in the THC have been reported from paleoclimatic records (e.g. Broecker et al. 1985), and it is currently discussed whether greenhouse warming may have a serious impact on the stability of THC (e.g. Cubasch et al. 2001). The North Atlantic SST varied on a wide range of timescales during the last century (e.g. Deser and Blackmon 1993). It has been pointed out (Bjerknes 1964) that the short-term interannual variations are driven primarily by the atmosphere, while the long-term multi-decadal changes may be forced by variations in ocean dynamics. The latter is supported by simulations with coupled ocean-atmosphere models (Delworth et al. 1993, Timmermann et al. 1998) which show that variations in the North Atlantic THC reflect themselves in large-scale SST anomalies. Recently, consistency between the observed multi-decadal SST variability derived from paleo-climatic and instrumental data and that simulated by two versions of the Geophysical Fluid Dynamics Laboratory (GFDL) coupled model has been demonstrated (Delworth and Mann 2000).

Changes in the THC strength may have strong implications for global and regional climates (e.g. Manabe and Stouffer 1999). However, up to present, there exists no means to observe the variability of the THC. Here, we present a method to reconstruct past variations of the THC and to monitor the state of the North Atlantic climate system in the future by simply observing Atlantic SSTs. Additionally, we systematically explore the predictability of the North Atlantic climate system. A large body of literature exists on the SST variability of the Atlantic. The existence of multi-decadal SST variability with opposite signs in the North and South Atlantic and its impact on Sahelian rainfall was described by Folland et al. 1984, Folland et al. 1986. The multi-decadal SST variability in the Atlantic Ocean has also been described in many subsequent papers (e.g. Delworth and Mann 2000, and references therein). Our paper is organised as follows. The multi-decadal variability in North Atlantic SST is described in section 2 and the origin of this variability is investigated in section 3. We present the results of the classical predictability experiments in section 4 and those of the greenhouse warming simulations in section 5. The paper is concluded with a summary and discussion of the major findings.

## 2 Multi-decadal SST variability

We analyse first the latest Hadley Centre SST dataset which covers the period 1870-1998. This dataset is partly described in Folland et al. 1999. The monthly values were averaged to annual mean values, which is justified, since we concentrate here on the multi-decadal timescale. Coupled model simulations with and without ocean dynamics (not shown) indicate that one of the regions of strong influence of the ocean dynamics on SST is the North Atlantic between 40-60$^{o}$N. We therefore define an SST index which averages the SST over the region 40-60$^{o}$N and 50-10$^{o}$W. This index shows some rather strong multi-decadal variability (Fig. 1), with anomalously high SSTs around 1900 and the 1950s and increasing SSTs during the most recent years. Also shown is the low-pass filtered version of the North Atlantic SST index using a 21-year running mean filter. It is noted that the SST index does not correspond well to the North Atlantic Oscillation (NAO) index (see e. g. Hurrell 1995), a measure of the westerlies over the North Atlantic, which suggests that the North Atlantic SST variability is not simply a response to the low-frequency variations in the NAO. As will be shown below by discussing model results, the type of multi-decadal variability considered here originates in the ocean. Furthermore, we would like to point out that the North Atlantic SST index does not exhibit any strong trend during the last several decades, but shows instead a rather oscillatory behaviour throughout the analysed period.

We computed the spatial anomaly structure of North Atlantic SST that goes along with the multi-decadal variability (not shown). It is rather homogeneous and was discussed, for instance, by Delworth and Mann (2000), Folland et al. (1984) and Folland et al. (1986): Anomalies of the same sign cover basically the whole North Atlantic Ocean from the equator to the high latitudes, with strongest values near 60$^{o}$N. Anomalies of opposite sign are found in the South Atlantic (not shown). This SST anomaly pattern associated to the multi-decadal variability is strikingly different to the characteristic SST anomaly pattern associated with the higher-frequency interannual variability. The latter is characterised by the well-known North Atlantic tripolar SST anomaly pattern (Visbeck et al. 1998) which is forced by the atmosphere through surface heat flux anomalies associated with the NAO. Thus, the multi-decadal SST variability in the North Atlantic exhibits a unique spatial structure. In order to investigate the dynamics of the multi-decadal SST variability further, we analyse next the results from an extended-range integration with our global climate model.

The model used in this study to explore the dynamics of the multi-decadal SST variability is the new Max-Planck-Institute for Meteorology global climate model. The ocean component MPI-OM1 (Marsland et al. 2002) is based on a C-grid version of the HOPE (Hamburg Ocean Model in Primitive Equations) ocean model and employs variable horizontal resolution, with relatively high resolution (~10-50km) in the high latitudes and near the equator. The atmosphere model is ECHAM5, the latest cycle of the ECHAM (European Centre HAMburg) atmosphere model. It is run at T42 resolution which corresponds to a horizontal resolution of about 2.8$^{o}$ x 2.8$^{o}$. A high vertical resolution version of ECHAM5 has been used by Giorgetta et al. (2002) to study the dynamics of the stratospheric quasi-biennial oscillation (QBO). A Hibler-type dynamic/thermodynamic sea ice model and a river run off scheme are included in the climate model. Glacier calving is treated in a simple but interactive manner. The climate model does not employ flux adjustments or any other corrections. Here a 400 year long control integration with the model is analysed. The model simulates the present-day climate of the North Atlantic realistically. The climate model's thermohaline circulation is consistent with observations, with a maximum overturning of about 20 Sv and a northward heat transport of about 1 PW at 30$^{o}$N (Marsland et al. 2002).

The model simulates the tripolar SST anomaly pattern in the North Atlantic at interannual timescales, and consistent with observations, it is forced by the NAO (not shown). The model also simulates pronounced multi-decadal variability in North Atlantic SST. The same North Atlantic SST index that was computed from the observations was derived from the model simulation (Fig. 1). The figure demonstrates that after some initial rapid adjustment, the model oscillates with a multi-decadal timescale similar to that observed. However, the SST fluctuations simulated by the model appear initially to be somewhat larger than those observed. In order to highlight the multi-decadal variability, the 21-year running mean is also shown in Fig. 1. Next, we computed

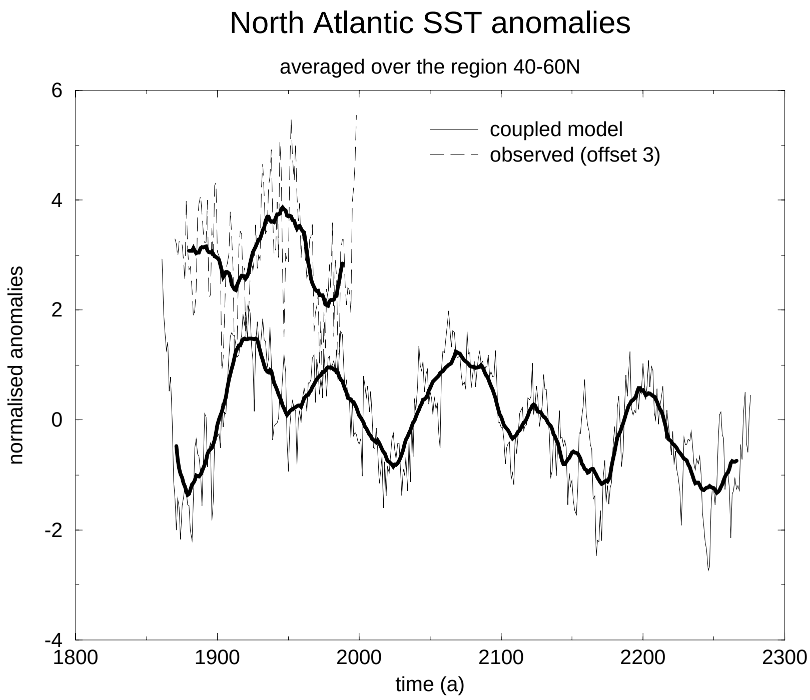


*Figure 1: Time series of the observed (dashed curve) annual North Atlantic SST anomalies averaged over the region 40-60$^o$N and 50-10$^o$W and the corresponding simulation (solid line). The thick curves are the corresponding 21-year running means which highlight the multi-decadal variability. The time series were normalised with their respective standard deviations.*

the spatial pattern associated to multi-decadal variability of the model (not shown). The model SST anomaly pattern associated to the multi-decadal variability is consistent with that derived from the observations and also characterised by a rather homogeneous pattern in the North Atlantic. Although some small regional differences exist between the observed and simulated patterns, we conclude that our climate model simulates realistically the multi-decadal variability in the North Atlantic, so that it can be used to study the origin of the SST variability.

## 3 Origin of the multi-decadal SST variability

The climate model offers us the possibility to investigate the physics behind the multi-decadal SST changes. An investigation of the model's thermohaline circulation and North Atlantic SST revealed that both are closely related to each other (Fig. 2). Specifically, the strength of the meridional overturning at 30$^o$N correlates almost perfectly with the North Atlantic SST index defined above at timescales beyond several years. This suggests that the multi-decadal SST fluctuations are driven by ocean dynamics, which is also supported by the investigation of the surface heat flux anomalies. The latter are strongly anti-correlated with the SST anomalies which is demonstrated by the cross correlation function between North Atlantic SST and surface heat flux anomalies

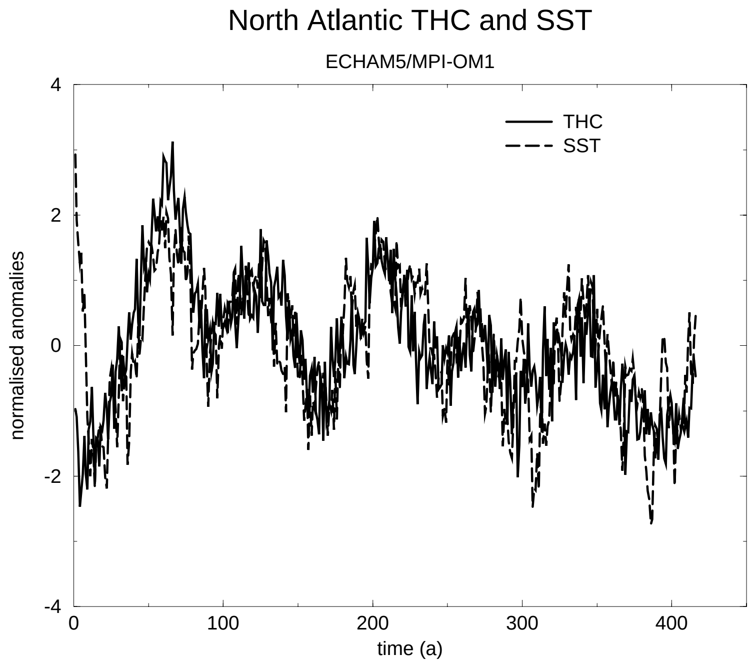


*Figure 2: Time series of simulated annual mean North Atlantic SST anomalies (40-60°N and 50-10°W, dashed line) and annual mean anomalies of the maximum overturning at 30°N (full line), a measure of the strength of the model's thermohaline circulation. Note that both time series are highly correlated at timescales beyond several years indicating that the low-frequency variations of the THC can be monitored by SSTs. Both time series were normalised with their respective standard deviations.*

(Fig. 3a), which exhibits the strongest negative correlations near zero lag. Thus, the surface heat flux can be regarded as a damping for the SST anomalies, a result that is also supported by observations (WOCE Report 2001).

A clear connection of the SST anomalies, however, is found to the northward oceanic heat transport. The ocean heat transport leads the North Atlantic SST by several years, as shown by the cross correlation between the meridional ocean heat transport and the SST anomalies (Fig. 3b). The heat transport has a thermohaline and a wind-driven part. We investigated the relative roles of the two components of the ocean heat transport for the SST variability. We found that the wind-driven part is only relevant at shorter timescales of several years and that, on the multi-decadal timescale, it is the thermohaline part that dominates. Our results are also consistent with modelling studies investigating the stability of the THC (Manabe and Stouffer 1988, Schiller et al. 1997). In particular, the SST response to a shutdown of the THC shows large similarities to the SST anomaly pattern discussed above.

The close connection between THC strength and SST variability can be used to either reconstruct changes in the THC from SST observations or to monitor the state of the THC in the future. If our model mimics the real relationship between THC and SST correctly, the observed changes in North Atlantic SST (Fig. 1) can be interpreted as changes in the THC strength: Decade-long positive anomalies in the North Atlantic SST index can be regarded as indicators for an anomalously strong THC and vice versa. In particular, the strong cooling during the period 1960-1990 may just as well be related to an anomalously weak THC as part of an internal oscillation than to anthropogenic factors, as hypothesized by some authors (e.g. Hegerl et al. 1997), since the cooling is replaced by a warming during the most recent years.

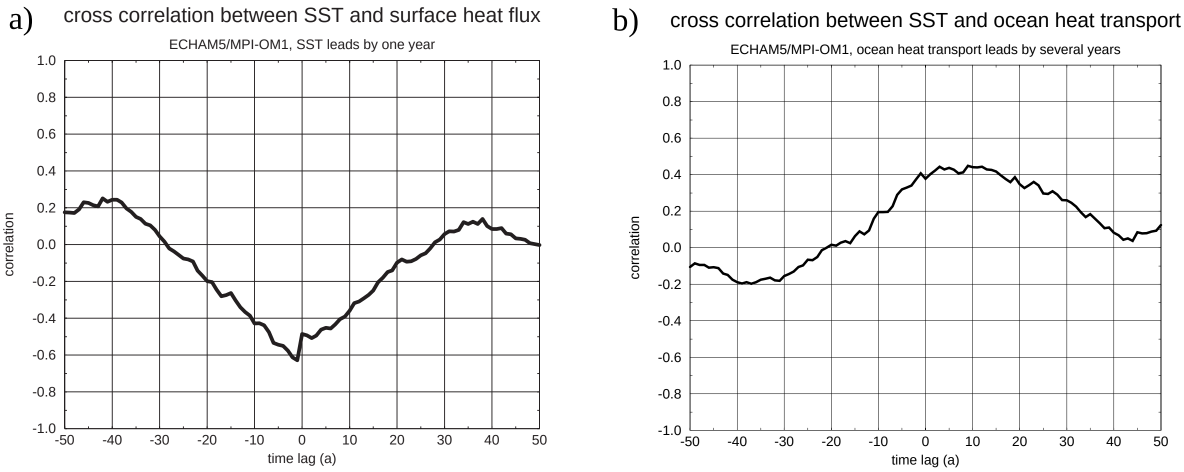


*Figure 3: a. Cross correlation of the North Atlantic SST anomalies (shown in Fig. 1) and the surface heat flux anomalies averaged over the same region as function of the time lag (a). Please note that the SST and the heat flux are negatively correlated, so that the heat flux can be regarded as a damping for the SST anomalies. b) Cross correlation of the North Atlantic SST index with the northward ocean heat transport at 30$^o$N as function of the time lag (a). Maximum correlation is found at positive time lags, which indicates the ocean heat transport leads the SST. This demonstrates together with the left panel that it is the ocean dynamics that drive the SST.*

# 4 Classical predictability experiments

We have shown that the multi-decadal variability in SST is closely related to the variability of the North Atlantic thermohaline circulation (e. g. Figs. 2 and 3). This indicates that the SST variations may be predictable, even beyond interannual timescales. In order to explore the predictability of the SST, we conducted an ensemble of classical predictability experiments with our global climate model. We have chosen two states from the control integration, perturbed the atmospheric initial conditions and restarted the model. We did not perturb the oceanic initial conditions, so that our predictability estimates may be regarded as upper limits of the predictability. Each perturbation experiment has a duration of 20 years, and we conducted an ensemble of 6 perturbation experiments for each of the two initial states. This yields a total integration time of 240 years.

The results of the predictability experiments are summarised in Fig. 4. A predictability measure was defined as P = 1 - (E/C). Here E is the variance between the ensemble members and C the variance of the control integration. If the spread between the individual ensemble members is small compared to the internal variability of the coupled system, the predictability measure is close to unity, indicating a high level of predictability. If, on the other hand, the spread is comparable to the internal variability, the predictability measure is close to zero and predictability is lost. Our predictability experiments indicate that the North Atlantic SST is highly predictable. The predictability measure stays well above zero for all twenty years in both ensembles. Thus, the North Atlantic SST is predictable even at decadal timescales. We investigated also whether predictability exists in atmospheric quantities (not shown). The results are less impressive than those for SST, but predictability in sea level pressure, for instance, exists for at least a few years. Interestingly, the multi-decadal variability discussed here projects most strongly onto the so called East Atlantic Pattern (EAP) and not onto the NAO. Consequently, we find slightly higher predictability for the EAP relative to the NAO.

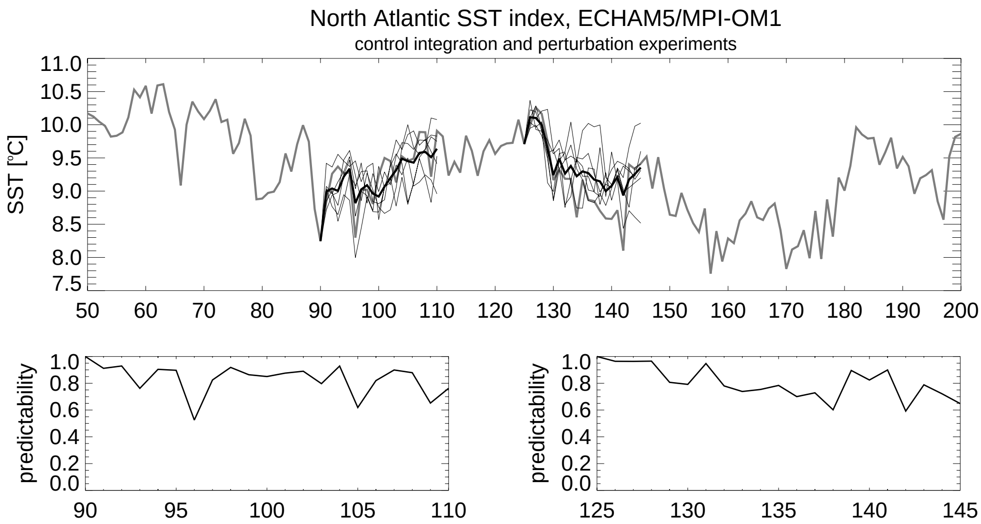


*Figure 4: Results of the classical predictability experiments with the global climate model. Upper panel: Time series of the North Atlantic SST index for years 50-200 of the control integration (grey line). Superimposed are the SST indices simulated in the perturbation experiments (thin lines). The thick black curves denote the ensemble means. Lower panels: Evolution of the predictability measure as function of the lead time (a). Note that the changes in the North Atlantic SST index are predictable a few decades ahead.*

# 5 Greenhouse warming simulations

The SST anomaly pattern associated with the THC variability can also be used as a fingerprint to detect future changes in THC intensity. Many authors have reported a weakening of the THC in global warming simulations (see e.g. Cubasch et al. 2001, Rahmstorf 1999), which may have strong impacts on the climate of the North Atlantic/European sector. However, it is unclear how such a change in THC intensity can be observed. Our model results suggest that an easy means to monitor the THC strength can be obtained simply by observing Atlantic SSTs. However, in the presence of global warming a differential SST index which measures the contrast between the North and South Atlantic has to be used. In order to test this hypothesis, an additional ensemble of three greenhouse warming simulations was conducted (Fig. 5a). For this purpose the climate model was initialised from different states of the control integration that are 30 years apart from each other (years 30, 60 and 90), and the atmospheric $CO_2$ content was increased by 1% per year (compound). The results are analysed for the longest integration (110 years), initialised in year 60 in which the $CO_2$ concentration triples, and they confirm the hypothesis that changes in THC strength can be seen in the differential Atlantic SST index (Fig. 5b).

The results also show that the THC evolution in the greenhouse warming simulations closely follows that of the control run for some decades before diverging from it (Fig. 5a). This behavior is markedly different from that of global mean surface temperature which exhibits a rather monotonic increase in all members. This implies a strong sensitivity to initial conditions but also a great deal of predictability of the multi-decadal variability in the North Atlantic, provided the initial state is well known. These results are consistent with our classical predictability experiments discussed above. Furthermore, our results imply that anthropogenically forced changes in THC strength may be masked for quite a long time by the presence of the internal multi-decadal variability. The next several decades may therefore be dominated by the internal multi-decadal variability, and we have to consider a joint initial/boundary value problem when assessing how the THC will evolve

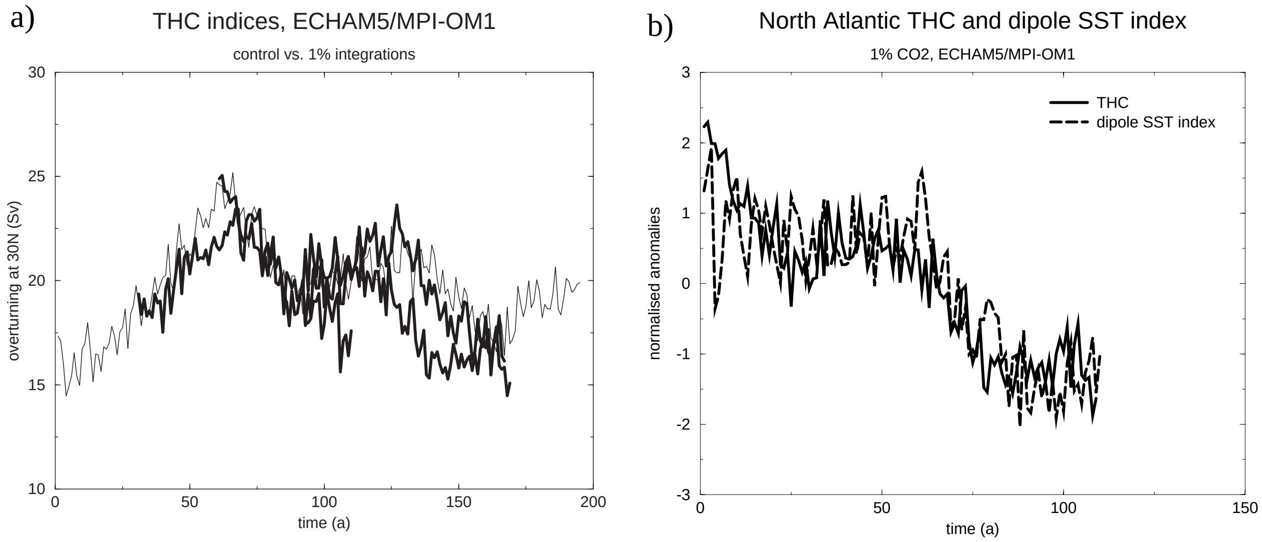


*Figure 5: a. Time series of the annual mean anomalies of the maximum overturning (Sv) at 30°N in the control integration (thin grey line) and in the greenhouse warming simulations (black thick lines). Note that the evolutions in the greenhouse warming simulations closely follow those of the control integration for several decades, indicating a very high level of THC predictability. b. Time series of the simulated annual mean Atlantic dipole SST index (dashed line) and annual mean anomalies of the maximum overturning at 30°N (full line) in the longest of the greenhouse warming simulations. The dipole SST index is defined as the difference between North Atlantic (40-60°N and 50-10°W) and South Atlantic (10-40°S and 30°W-10°E) SST. Note that SST and overturning are highly correlated at timescales beyond several years in the greenhouse warming simulation. This implies that future changes in the THC can be monitored by observing SSTs. The time series were normalised with their respective standard deviations.*

during this century. Greenhouse gas simulations should therefore be properly initialised using present-day ocean conditions and they should be conducted in ensemble mode to assess the uncertainty.

## 6 Summary and Discussion

A close relationship exists between multi-decadal variations in the strength of the North Atlantic thermohaline circulation and Atlantic sea surface temperature. This has been shown by means of simulations with a global climate model which realistically simulates the multi-decadal SST variability in the North Atlantic. The same relationship was found in another climate model (ECHAM4/OPYC, not shown) which was used by Latif et al., 2000, for instance, to discuss the stability of the THC in a greenhouse warming simulation. The link between THC strength and SST can be exploited to reconstruct past and to monitor future changes in the strength of the THC using SSTs only. Since SSTs are observable from space using passive microwave techniques, they are readily available in near real-time with good spatial and temporal coverage. Thus, the low-frequency variability of a major component of the large-scale ocean circulation, the North Atlantic thermohaline circulation, can be determined from the already existing ocean observing system.

These results are also important in view of the predictability of the North Atlantic climate system at decadal timescales. As shown by analysing the results of the classical predictability experiments and the ensemble of greenhouse warming simulations, the North Atlantic thermohaline circulation exhibits a relatively high degree of predictability at decadal timescales, which is consistent with earlier predictability studies (Griffies and Bryan 1997, Grötzner et al. 1999). Predictability, however, depends on the availability of the initial state. The relationship between variations in THC and SST found in our climate model can also be exploited for predictability purposes, as the initial oceanic state can be estimated from the history of SST. A simple statistical scheme, for instance, can be envisaged to reconstruct the multi-decadal variations in the oceanic density structure by projecting the multi-decadal SST fluctuations onto the three-dimensional oceanic density field using a model-derived statistical transfer function. These reconstructions can then easily be used in a data assimilation procedure to produce an ocean analysis from which the decadal predictions can be initialised. If skilful, such predictions of decadal changes in the THC would not only be of enormous scientific but also large public interest, since they would have a large economic value.

However, more model studies on this subject are necessary. Here we conclude that the potential may exist to reconstruct, monitor and predict decadal changes in the North Atlantic climate using only surface observations. The situation may be similar to that of predicting the El Niño/Southern Oscillation (ENSO) phenomenon (Philander 1990) on interannual timescales. ENSO predictability can also be achieved by using only surface information (e.g. Segschneider et al. 2000, Oberhuber et al. 1998).

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