Tropical Pacific/Atlantic Ocean Interactions at Multi-Decadal Time Scales

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Analysis of sea surface temperature (SST) observations suggests a pan-oceanic interaction between the tropical Pacific and the Atlantic Ocean at multi-decadal time scales, such that periods of anomalously high SSTs in the eastern tropical Pacific are followed by a basin-wide SST dipole in the Atlantic Ocean with a time delay of a few decades. The SST anomaly structure in the Atlantic Ocean is reminscent of variations in the North Atlantic thermohaline circulation. The two ocean basins are linked through an “atmospheric bridge” involving anomalous fresh water fluxes. Based on the observational findings, the Atlantic thermohaline circulation may strengthen during the next decades in response to the strong decades-long increase in eastern tropical Pacific SST, which will have strong impacts on the climates of North America and Europe through changes in the North Atlantic Oscillation (NAO).

The Atlantic Ocean exhibits considerable multi-decadal variations, as described in many observational and modeling papers (e. g. Folland et al. 1986, Deser and Blackmon 1993, Delworth et al. 1993, Kushnir 1994, Mann and Park 1996, Dickson et al. 1996, Curry et al. 1998, Timmermann et al. 1998). Multi-decadal variations are also observed in the tropical Pacific (e. g. Graham 1994, Trenberth and Hurrell 1994, Zhang et al. 1997). So far, it has been mostly assumed that the multi-decadal variations in the two ocean basins evolve independently from each other. However, time series of the equatorial Pacific SST anomaly (averaged over the Niño-3 region, 5^oN-5^oS, 150^oW-90^oW, and derived from the Kaplan SST dataset (Kaplan et al. 1997)) and the North Atlantic Oscillation index (NAO index, a measure of the westerlies over the North Atlantic (Hurrell 1995)) show a remarkable correspondence of the two time series at multi-decadal time scales (Fig. 1). In the following it is shown how the two ocean basins may be linked to each other.

It has been shown in a recent paper (Latif et al. 2000) that changes in the tropical Pacific stabilise the North Atlantic thermohaline circulation (THC) in a greenhouse warming simulation, with the atmosphere serving as a coupling device between the two oceans. The proposed mechanism works as follows: The long-term changes in the eastern tropical Pacific SST induce changes in the fresh water flux over the tropical Atlantic, which will lead to anomalous sea surface salinities (SSSs) in the tropical Atlantic Ocean. The SSS anomalies are advected poleward by the mean ocean circulation, eventually affecting the density in the sinking region of the Northern Hemisphere, thereby affecting the convection and the strength of the thermohaline circulation.

Here observations are investigated to test whether the mechanism found in the model study of Latif et al. 2000 can be identified also in the real world. Since long observations with good spatial coverage exist only for SST, this study is restricted to the analysis of SST. Atmospheric general circulation model (AGCM) integrations are used additionally to demonstrate the existence of an atmospheric bridge, connecting the eastern tropical Pacific and Atlantic Oceans. It is noted, however, that SST observations exist only for about the last 150 years. Thus, any investigation of multi-decadal variability will suffer seriously from the too short records. The results, however, are statistically significant.

The El Niño/Southern Oscillation (ENSO) phenomenon is the strongest natural climate fluctuation on interannual time scales (see the text book of Philander 1990 for details on ENSO). ENSO, although originating in the tropical Pacific, has global climatic impacts, and it has been shown by Schmittner et al. 2000 that changes in the fresh water flux over the tropical Atlantic Ocean are strongly correlated with ENSO: Anomalously high (low) SSTs in the eastern tropical Pacific go together with an anomalously low (high) fresh water input into the tropical Atlantic. As outlined by both Latif et al. 2000 and Schmittner et al. 2000 these changes in the Atlantic fresh water budget may lead to changes in the THC, if the changes in the fresh water flux persist sufficiently long.

Unfortunately, long time series of the fresh water flux over the Atlantic are not available from observations. Instead AGCM simulations with observed SSTs prescribed globally for several decades were used to study the connections between the tropical Pacific and tropical Atlantic

Oceans. The tropical atmosphere is highly predictable (e. g. Lau 1985), and it is believed that such simulations provide useful insights about the nature of the response of the tropical atmosphere to tropical Pacific SST anomalies associated with ENSO-type decadal variability. The AGCM used here is ECHAM4 (Roeckner et al. 1996) with T42 resolution (2.8^o x 2.8^o), a model that has been used in many climate applications (see e. g. Roeckner et al. 1999). An ensemble of three AGCM integrations was performed for the period 1903-1994, and the ensemble mean is shown here. Please note that the SSTs used to drive the model are the GISST SSTs (Parker et al. 1995) and not the Kaplan SSTs shown in Fig. 1. The latter are used in the investigation of the SSTs shown below, since it is the longer dataset. However, since the response characteristics of the model do not depend on the forcing SSTs, the use of the different SST datasets in this study is justified.

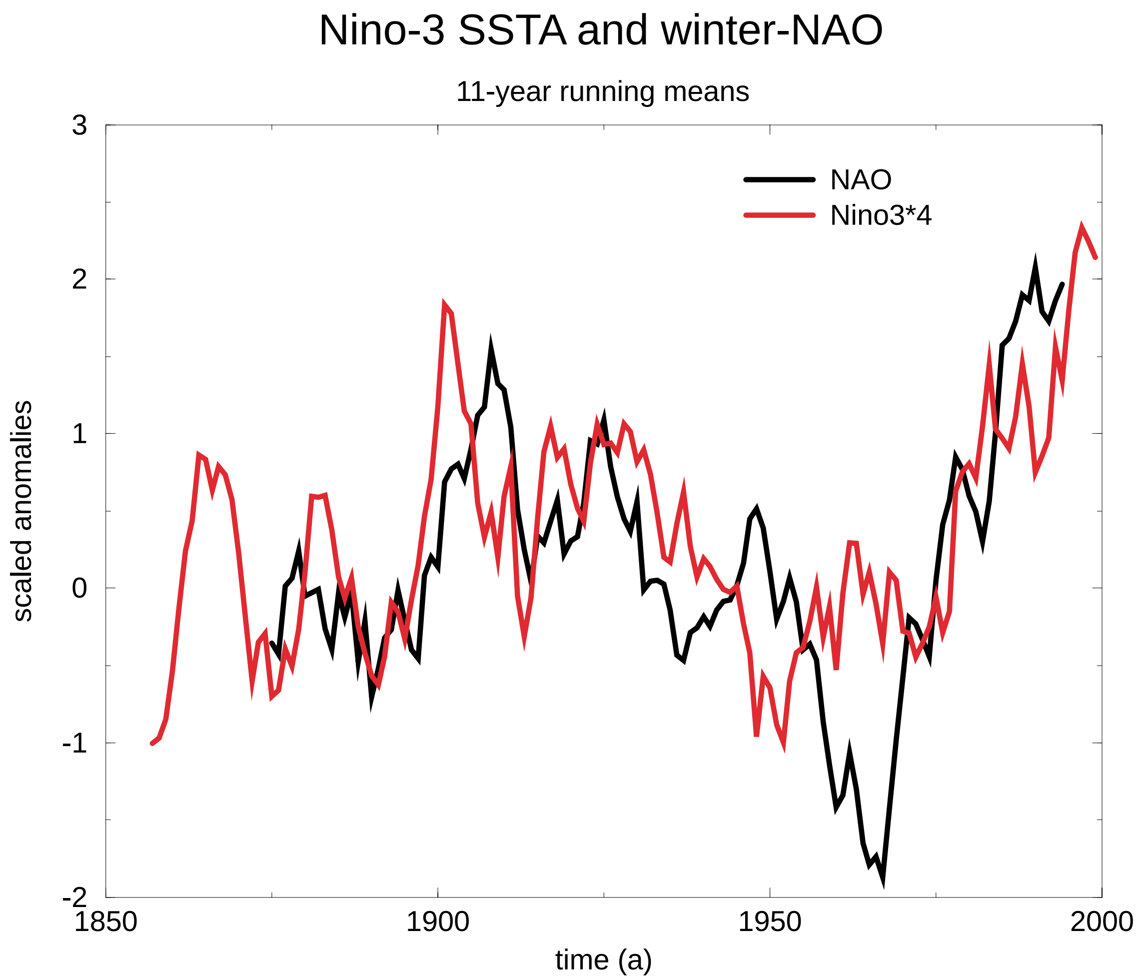

Fig. 1: Time series of the Niño-3 SST anomaly and the North Atlantic Oscillation (NAO) index. Both time series are highly coherent at multi-decadal time scales. Both time series were filtered with a 11-year running mean.

The atmosphere model simulates an out-of-phase relationship between decadal fluctuations in eastern tropical Pacific (Niño-3) SST and the fresh water flux over the tropical Atlantic (10^oS-30^oN) as shown in Fig. 2, confirming the observational results of Schmittner et al. 2000. The correlation between the two time series amounts to -0.75. Furthermore, both the tropical Pacific SST and the simulated fresh water flux exhibit rather strong trends during the last 50 years: While the tropical Pacific SST is slowly increasing (see also Fig. 1) by about 0.5^oC, the fresh water flux over the tropical Atlantic is slowly decreasing by about 0.06 Sv ($10^6 m^3/s$). This behaviour is consistent with that found in the greenhouse warming simulation by Latif et al. 2000 and supports the picture that there exists a potential "atmospheric bridge", by which the tropical Pacific and Atlantic Oceans can interact with each other. Furthermore, the trends shown above may continue in response to greenhouse warming as hypothesised by Latif et al. 2000.

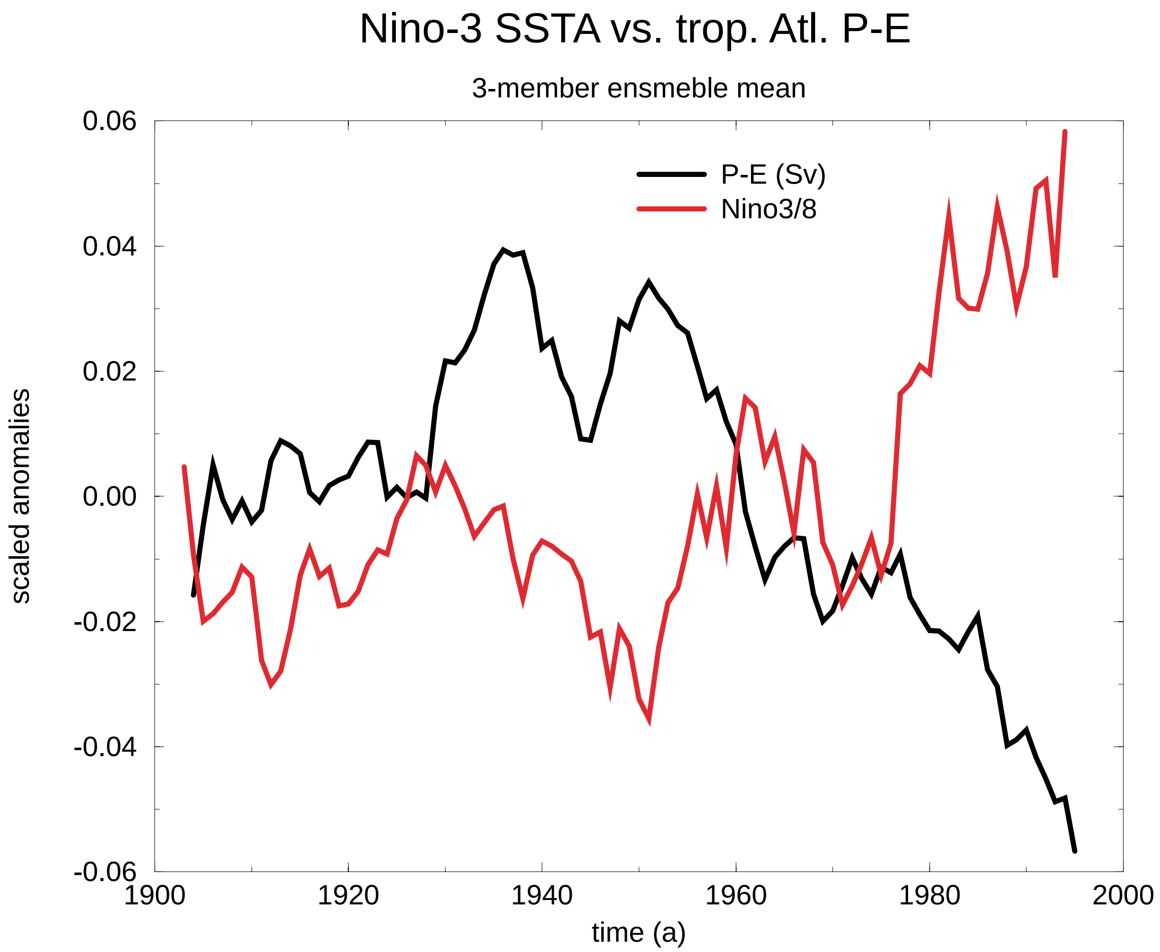

Fig. 2: Time series of the Niño-3 SST anomaly and the anomalous tropical Atlantic fresh water flux averaged over the region 10^oS-30^oN, which is the region with the most consistent response over the Atlantic. Both time series vary out of phase and exhibit strong trends during the last 50 years. Both time series were filtered with a 11-year running mean.

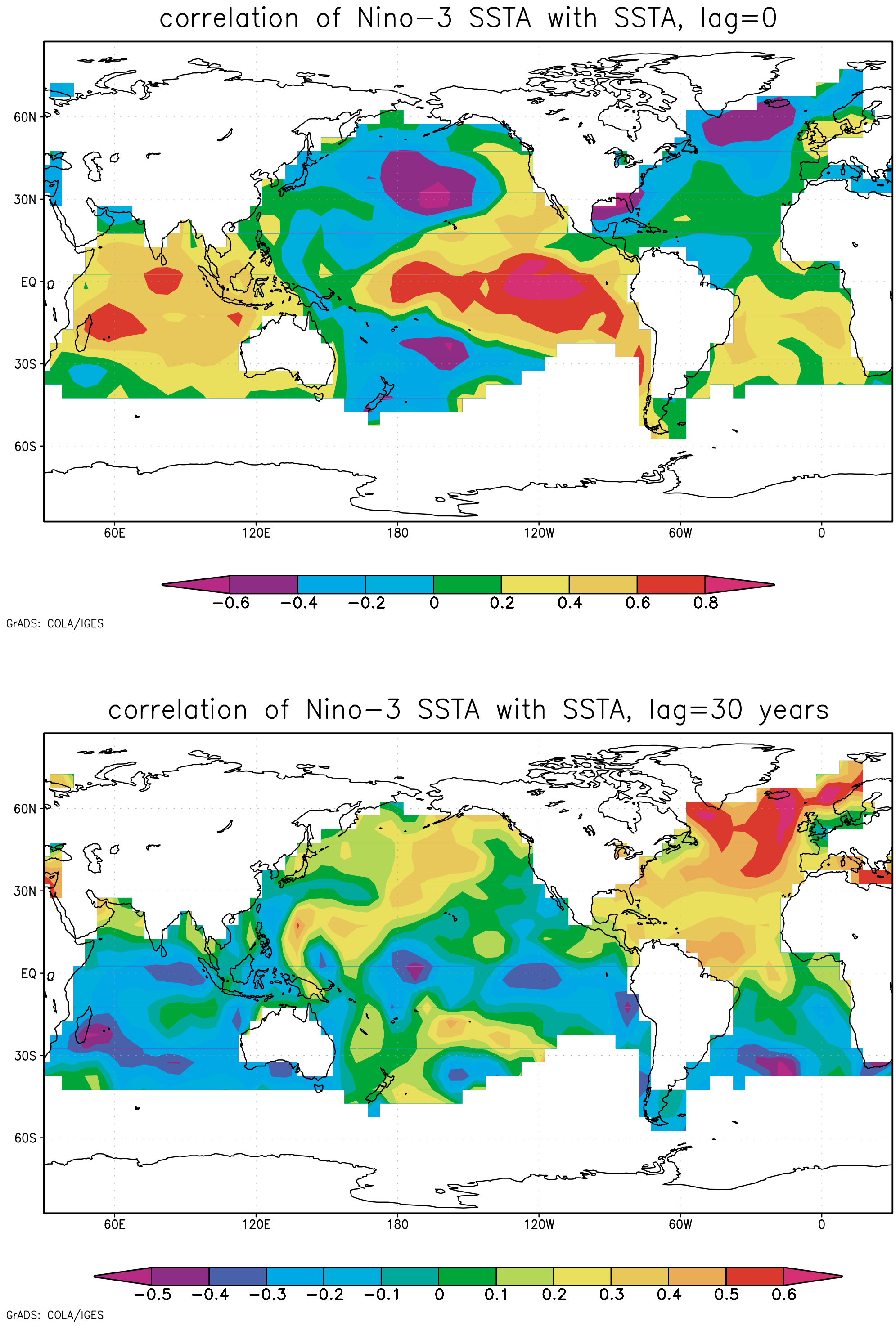

Fig. 3: a) Spatial distribution of correlation coefficients between the Niño-3 SST anomaly time series and the global SST anomalies at zero lag. b) Spatial distribution of correlation coefficients between the Niño-3 SST anomaly time series and the global SST anomalies at lag of 30 years. The anomaly structure in b) is reminiscent of variations in the THC, indicating that variations in the THC follow variations in tropical Pacific SST with a time lag of 30 years. The data were low-pass filtered with a 11-year running mean prior to the correlation analyses.

In the next step, it is investigated whether the THC in the Atlantic responds to the variations in the fresh water flux. This can be done only indirectly by using SSTs, since the required direct observations of the fresh water flux, surface salinity, and the THC do not exist. Ocean model and coupled model studies have shown that variations in the THC are associated with changes in the poleward ocean heat transport and an interhemispheric SST dipole (see e. g. Manabe and Stouffer 1999 and references therein). Thus, this characteristic SST anomaly pattern can be used as a “fingerprint” to identify variations in the real THC. A correlation analysis was conducted using the Kaplan SST dataset. First, the zero-lag correlation of the low-pass filtered tropical Pacific (Niño-3) SST anomaly time series with the global SST anomaly field has been computed. The resulting correlation pattern (Fig. 3a) shows the well known picture in the tropical Pacific, with an El Niño-like positive signal in the eastern and central equatorial Pacific and negative anomalies in the mid-latitudes of both hemispheres. A teleconnection to the Indian Ocean can be seen also, a feature known from present-day El Niño events. Strong negative correlations are found in the North Atlantic near Greenland, which is consistent with the evolution of the North Atlantic Oscillation (Fig. 1).

Based on the arguments described above, the time it will take to develop sufficiently strong salinity anomalies and to transport those poleward into the so called “sinking region” in the high latitudes is of the order of a few decades. Therefore, a time lag of 30 years has been introduced in the correlation analysis. The results of this lagged correlation analysis (Fig. 3b) exhibit strongest signals in the Atlantic Ocean, although a tropical Pacific SST index has been used as reference. The SST anomaly pattern is the interhemispheric dipole identified in model studies to go along with changes in the THC. Anomalously warm temperatures are found in the northern part and anomalously cold temperatures in the southern part of the Atlantic Ocean. Thus, the results indicate that interdecadal changes in tropical Pacific SST are followed by basin-wide changes in Atlantic SST, and that periods of high (low) SSTs in the eastern tropical Pacific are followed by a strong (weak) THC in the Atlantic. The statistical significance of the results was tested using a t-test and assuming 10 degrees of freedom, and correlations above about 0.5 are significant at the 95% level. More important than the level of the significance, however, is the fact that physically motivated SST anomaly patterns result from the two correlation analyses.

How are the changes in the thermohaline circulation related to the changes in the atmosphere, specifically the NAO? Fig. 1 indicates some connection between the Nino-3 SSTA and the NAO at multi-decadal time scales. Although a detailed investigation of the atmospheric response to the changes in the North Atlantic SST is beyond the scope of this paper, some plausibility arguments can be made. First, it is reasonable to assume that the response time of the atmosphere is short relative to the dominnant time scales on which the thermohaline circulation changes. Thus, the low-frequency changes in the North Atlantic SST and the changes in the NAO should evolve simultaneously. Second, the NAO will respond to the changes in the meridional temperature gradient in the Atlantic. A situation as given by Fig. 3b, which corresponds to a strong thermohaline circulation, is likely to be connected with a weak NAO, since the oceanic heat transport is enhanced, so that the atmosphere has to transport less heat poleward, which would lead to fewer storms and eventually to a weaker NAO. A simple forecast model which predicts the low-frequency changes in the NAO can therefore be constructed by exploiting the lead-lag relationship between the tropical Pacific and Atlantic SST anomalies and by assuming an out-of-phase relationship between variations in the North Atlantic thermohaline circulation and the NAO. This amounts to a forecast model that predicts the NAO by means of the past tropical Pacific SST anomalies. The results of such a simple forecast model using the low-pass filtered Niño-3 SST anomaly as a predictor (Fig. 1) and assuming a time lag of 35 years are shown in Fig. 4. Given the simplicity of the forecast model, its success is remarkable. It should be pointed out, however, that the variations in the tropical Pacific can explain only some part of the low-frequency variability in the NAO and that it is likely that interactions over the Atlantic will also contribute to the variability of the NAO. Based on the simple forecast scheme the NAO will weaken considerably during the next few decades.

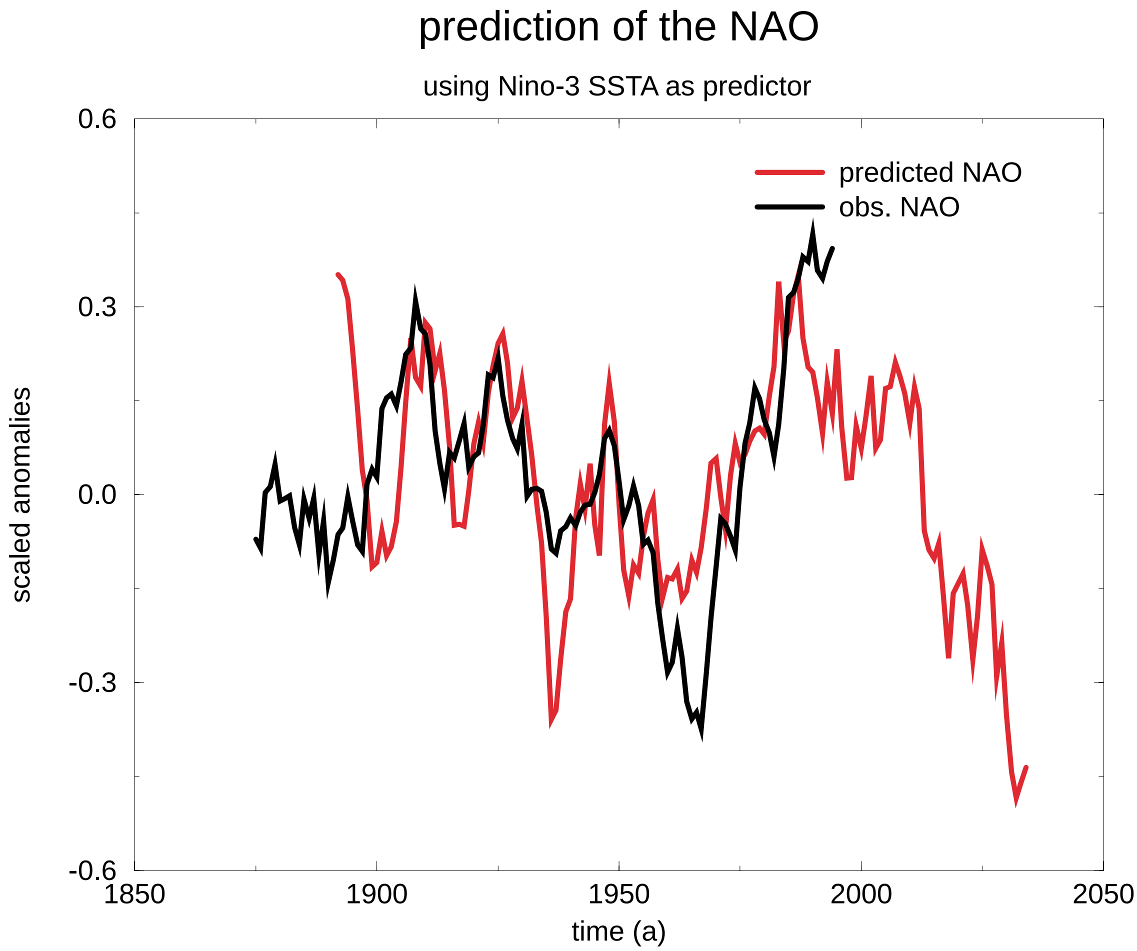

Fig. 4: Time series of the observed winter NAO index (low-pass filtered with a 11-year running mean) and the predicted NAO using the tropical Pacific SST anomalies averaged over the Ninño-3 region as predictor and assuming a time lag of 35 years. Both time series have been scaled for display purposes.

In summary, the results of this short investigation indicate that pan-oceanic interactions exist between the tropical Pacific and the Atlantic Oceans. The connection between the two ocean basins is provided through anomalies in the fresh water flux, as originally hypothesised by Latif et al. 2000 analysing a greenhouse warming simulation. Since the SST fluctuations in the tropical Pacific are highly predictable, the found lead-lag relationship implies also that the states of the THC and NAO may be predictable at multi-decadal time scales. Based on the results presented here, it may be speculated that the North Atlantic thermohaline circulation will strengthen during the next decades in response to the rapid increase of the eastern tropical Pacific SST observed during the recent decades. This will lead to a weakening NAO, which will have strong impacts on the climates of North America and Europe. However, it should be pointed out again that the observed database is so inadequate that large uncertainties remain in the description of pan-oceanic interactions at multi-decadal time scales.

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