North Atlantic Ocean control on surface heat flux on multidecadal timescales

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Nearly 50 years ago Bjerknes1 suggested that the character of large-scale air–sea interaction over the mid-latitude North Atlantic Ocean differs with timescales: the atmosphere was thought to drive directly most short-term—interannual—sea surface temperature (SST) variability, and the ocean to contribute significantly to long-term—multidecadal—SST and potentially atmospheric variability. Although the conjecture for short timescales is well accepted, understanding Atlantic multidecadal variability (AMV) of SST2–7 remains a challenge as a result of limited ocean observations. AMV is nonetheless of major socio-economic importance because it is linked to important climate phenomena such as Atlantic hurricane activity and Sahel rainfall, and it hinders the detection of anthropogenic signals in the North Atlantic sector8–10. Direct evidence of the oceanic influence of AMV can only be provided by surface heat fluxes, the language of ocean–atmosphere communication. Here we provide observational evidence that in the mid-latitude North Atlantic and on timescales longer than 10 years, surface turbulent heat fluxes are indeed driven by the ocean and may force the atmosphere, whereas on shorter timescales the converse is true, thereby confirming the Bjerknes conjecture. This result, although strongest in boreal winter, is found in all seasons. Our findings suggest that the predictability of mid-latitude North Atlantic air–sea interaction could extend beyond the ocean to the climate of surrounding continents.

AMV is characterized by coherent changes in SST over the whole of the North Atlantic that are most pronounced in the extratropics with a period of 70–80 years11,12. In many climate models, AMV results from variations in the Atlantic Meridional Overturning circulation (AMOC) that are generated internally by the coupled ocean–atmosphere system itself. Some studies13, however, argue that radiative forcing by aerosols drives AMV, but the impact of aerosols on climate remains highly uncertain14. Although AMV has been shown to influence tropical climate15 and extratropical summer conditions in the North Atlantic sector16, the role of the mid-latitude SST variations in forcing a large-scale atmospheric response is controversial16,17. Nevertheless, there is some evidence from data and climate models that AMV forces coordinated variations in European and North American climate18–20 through the advection of heat and moisture released from the North Atlantic.

Air–sea heat exchange is at the core of the whole chain of processes by which the North Atlantic Ocean may influence the atmosphere. If mid-latitudinal decadal and longer-term variations in SST are driven largely by ocean dynamics, then increasing or decreasing SST results in enhanced or reduced heat release, respectively, from the ocean to the atmosphere. The opposite process dominates air–sea flux variability on short timescales21: increasing or decreasing air–sea fluxes extract heat from the ocean and imply a decrease or increase, respectively, in SST. To explicitly quantify the transition between the short-term SST variations forced by the atmosphere and long-term oceanic changes that may influence the atmosphere, one therefore has to investigate surface heat fluxes. However, in contrast to SST and air temperature, temporally homogeneous long time series of surface fluxes were not available as a result of only poorly sampled parameters needed for flux computations, especially before the 1950s22. Here we use a new data set of turbulent heat fluxes reconstructed for the period from 1880 onwards from exclusively voluntary observing ship (VOS) observations of surface meteorological variables. This long record enables us to explicitly test the Bjerknes conjecture with data.

An AMV index is computed by averaging detrended monthly SST anomalies over the Atlantic region 35–50° N (Fig. 1a). Although this region differs from those used for quantifying AMV previously2,23,24, SST-based AMV index defined for this region is highly correlated with alternative definitions (Supplementary Fig. 1 and Supplementary Table 1) and depicts strong multidecadal variability. The major motivation for choosing this region is the larger number of observations of meteorological variables used for reconstructing surface turbulent heat fluxes. Time series of surface turbulent heat fluxes for the North Atlantic from 1880 onwards and at 5° × 5° spatial resolution are derived from VOS observations by the procedure of homogenization of sampling, a simplified bulk algorithm for the computation of fluxes25, and a priori knowledge of the statistical distribution of surface turbulent heat fluxes26 (Methods). Climatological total (sensible plus latent) turbulent heat fluxes over the North Atlantic for the period 1880–2007 capture the well-known major features, specifically the maxima over the Gulf Stream and in the subpolar North Atlantic (Fig. 1a).

The AMV index and surface turbulent heat fluxes averaged over 5° boxes in the mid-latitude and subpolar North Atlantic were decomposed into long-term (multidecadal) and short-term (interannual to decadal) components (Methods). Multidecadal fluctuations in surface turbulent heat fluxes and the SST index (as given by 11-year running means) are positively correlated (Figs 1b and 2) over the western mid-latitudinal North Atlantic, with the largest correlations of 0.77 found southeast of Newfoundland, which is statistically significant at the 95% level (Methods). Thus, in this region and on multidecadal timescales, increasing or decreasing surface ocean temperature goes along with a respective increase or decrease in surface turbulent fluxes; that is, the ocean heats or cools the atmosphere, respectively. This pattern holds for both sensible and latent flux (Supplementary Fig. 2) and is very persistent throughout the year, with only minor variations in the correlation strength (Supplementary Fig. 3). Similar analyses performed with NOAA-CIRES 20th Century Reanalysis V2 (20CRv2)27 confirm this finding (Supplementary Fig. 4). The close association between large-scale SST anomalies and the local surface heat flux in this area is also consistent with modelling studies21,28.

According to previous diagnostic and modelling work25,28 and as outlined above, we note that, on interannual to decadal timescales, the interaction between the SST and surface heat flux is different from that on multidecadal timescales. In mid-latitudes, the atmosphere, as a fast dynamical system, determines short-period synoptic variations in the heat flux that drive the temperature of the upper ocean mixed layer. Furthermore, the intensity of the day-to-day (synoptic) activity in the...
North Atlantic mid-latitudes is closely linked to the North Atlantic Oscillation (NAO)\textsuperscript{23}, the leading mode of internal atmospheric variability in this region, which is strongly correlated with surface fluxes on short interannual to intra-decadal timescales\textsuperscript{24}.

Consistent with this notion, deviations of the AMV index and surface turbulent heat flux from their respective 11-year running means, representing the short-term variability, are negatively correlated over the North Atlantic (Fig. 1c). The strongest correlations, close to $-0.5$, are identified east of Newfoundland and in the southern Labrador Sea. This implies that stronger surface fluxes result in decreasing SST, whereas weaker fluxes result in increasing SST, which is especially pronounced during the cold season (Supplementary Fig. 3) when atmospheric synoptic variability is most intense. Short-term variations in North Atlantic SST and turbulent heat flux averaged over 35–50° N are in antiphase, especially during the periods from the 1930s to the early 1950s and after 1960 (Fig. 2). Our results for both long-term and short-term variability remain practically unchanged when the SST-based AMV index is derived by using alternative SST data or by removing the anthropogenic signal using regression of the local SST onto time series of global mean surface temperature (Supplementary Figs 5 and 6). The correlation for the long-term component is somewhat stronger during the second part of the record, whereas the anticorrelation of short-term variability is slightly stronger before 1970 (Fig. 2 and Supplementary Fig. 7). For the long-term record, whereas the anticorrelation of short-term variability is slightly stronger before 1970 (Fig. 2 and Supplementary Fig. 7). For the long-term component this is primarily due to the impact of the very beginning of the record before 1885 and can be also partly explained by the larger magnitude of interdecadal variation in both SST and surface fluxes during the last several decades (Fig. 2) and a slight displacement of the maximum correlation pattern eastward (Supplementary Fig. 7). The use of AMV indices based on alternative approaches for processing the SST data, including methods to remove anthropogenic signal, results in smaller differences in correlation between the first and second parts of the record (Supplementary Fig. 8).

The different character of air–sea interaction on multidecadal and interannual timescales is clearly demonstrated by cross-spectral analysis (Fig. 3). The spectra of North Atlantic SST and surface turbulent heat fluxes (Methods) both show a peak at a period of 50–70 years. Both multidecadal and interannual variations of SST and observationally based surface fluxes are highly coherent (Fig. 3). However, the phase lag between the two is very close to zero in the band 30–70 years and sharply switches to antiphase, with a phase of about 180° at periods smaller than decadal. Thus, there is a negative feedback such that multidecadal SST variations are damped by the surface heat fluxes, which in turn implies that the ocean heats or cools the atmosphere on these long timescales, a situation that exists on interannual timescales in parts of the Tropics, for example, the equatorial Pacific Ocean.

The timescale on which the character of air–sea interaction in the North Atlantic mid-latitudes changes qualitatively is clearly identified by the correlations between SST and surface heat fluxes calculated at different timescales and averaged over the mid-latitudinal North Atlantic (Fig. 4). The long-term components are highly positively
correlated and the short-term components show significant negative correlations (and field significance in this belt) when the length of the running mean window used to separate short-term and long-term components exceeds 10 years. When the length of the running mean is shorter than 10 years, the correlations for both long-term and short-term components weaken substantially, with the pattern lacking field significance (Methods).

Our analysis based on reconstructed time series of turbulent heat flux at the sea surface during 1880–2007 clearly shows that multidecadal variations in SST in the Gulf Stream extension region have an active role in air–sea interaction and thus in diabatic heating of the lower atmosphere. The link is strongest at periods of 50–70 years and is significantly associated with AMV, which is consistent with results from climate models in the absence of external forcing. On interannual timescales, however, the atmosphere, as expected, drives changes in SST, with cooling or warming of the surface ocean under the influence of intensified or weakened surface fluxes, respectively. The results are important in the context of climate predictability in the sense that the North Atlantic multidecadal SST changes may not only be predictable but may also drive a large-scale atmospheric response. This is not so for the shorter interannual and intra-decadal timescales, on which chaotic atmospheric variability drives SST.

We have considered here only the turbulent heat fluxes, which are known to contribute the largest share to the total (net) heat flux variability at the ocean’s surface. In future work it would be important to extend the analysis to the radiative components of air–sea heat exchange (short-wave and long-wave radiation fluxes) to complete the surface heat balance. This will particularly permit testing of the capabilities of external radiative forcing as a driving factor for AMV. However, reconstruction of the radiative fluxes requires estimates of cloud cover, which was poorly sampled before World War II. Our work nevertheless opens an interesting avenue for the analysis of the results of model simulations of the climate for the previous century and will help to design new experiments, extending earlier efforts and targeting the role of ocean signals in forcing atmospheric variability on multidecadal timescales in the North Atlantic and possibly also other ocean basins.

**METHODS SUMMARY**

We have reconstructed long-term time series of surface turbulent heat fluxes using individual VOS reports from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS, version 2.5) for the period 1880–2007. To minimize the impact of time-dependent sampling errors (Supplementary Figs 9 and 10) on the results, we subsampled the meteorological variables randomly, selecting 45 reports for each 5° grid cell in each season. Special selection procedures were used to minimize the impact of changes in observational practices on the results. Atmospheric humidity was reconstructed with a simple multivariate regression procedure based on the data for the period 1960–1980 (Supplementary Figs 11 and 12). Subsampling was repeated 20 times for each 5° grid cell and for each season (January–March, April–June, July–September and October–December). The robustness of the results with respect to the number of samples is discussed in Supplementary Fig. 10b. Surface fluxes were then computed from the subsampled data by using a simplified

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**Figure 3** | Cross-spectral analysis of the AMV SST index and anomalies of surface turbulent heat fluxes. Bottom: power spectra of the SST index (red) and surface turbulent sensible plus latent heat flux in the region shown in Fig. 2 (green). There is a pronounced peak at a roughly 60-yr period in both spectra. Top: squared coherence of SST AMV index and surface heat flux (orange) and phase lag between the time series (blue). A phase lag close to zero indicates that oscillations of SST and surface fluxes are in-phase, while a phase lag varying around 180° shows that the oscillation at a given frequency is in antiphase. For easier interpretation, ordinate labels change sign at 180°. Grey shading shows the range of negative phase lags. Thin dashed lines in both panels indicate 95% significance levels for spectral power and coherence. Frequencies on the x axis are in cycles per year (cpy); additionally, corresponding periods in years are indicated.

**Figure 4** | Changing correlations between the AMV SST index and anomalies of surface heat fluxes with the length of the filtering window. Correlation between anomalies of the AMV SST index and surface turbulent heat fluxes were estimated with different running mean lengths for the long-term component (magenta) and the short-term component (blue). Correlation coefficients were averaged over the area shown in Fig. 2; error bars indicate s.d. of coefficient values. Highly positive correlations between the long-term components and significantly negative correlations between the short-term components are persistent for the windows of 10 years and more, implying the timescale on which the interaction between SST and surface turbulent fluxes changes its character. The grey shaded band shows the range for which patterns of positive correlations for the long-term components and negative correlations for the short-term components hold field significance within the 35–50°N area.
version of the COARE-3.0 algorithm\textsuperscript{14} (20 sub samples). For each sub sample the modified Fisher–Tippett distribution\textsuperscript{15} was used to approximate the computed fluxes and was further integrated to obtain estimates of seasonal mean flux. Averaging over 20 random sub samples provided seasonal estimates of surface sensible and latent fluxes for a grid cell.

Decomposition of the 128-year time series of the detrended (Supplementary Figs 5 and 6) SST and surface heat fluxes into long-term (interdecadal) and short-term (interannual) components was performed by applying an 11-year running mean (or running mean over different smoothing windows; see Fig. 4 for example). The correlation analysis\textsuperscript{20} was performed for the detrended time series. Cross-spectral analysis was performed with the maximum entropy method\textsuperscript{21} on the basis of predicting the available data to infinite time by an autoregressive fitting (Supplementary Fig. 13).

**Full Methods** and any associated references are available in the online version of the paper.

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METHODS

Reconstruction of surface turbulent heat flux time series. To reconstruct long-term time series of surface turbulent heat fluxes in the North Atlantic we applied a methodology designed to minimize temporal inhomogeneities in sampling density and observational practices. We used individual VOS reports from the International Comprehensive Ocean–Atmosphere Data Set (ICODAS, version 2.5) for the period 1880–2007. Although North Atlantic mid-latitudes are generally better sampled with VOS observations than other regions of the World Ocean, there is a strong inhomogeneity in the number of samples through the years with the number of observations in the 1880s–1900s being 10–20-fold smaller than in the 1960s–2000s (Supplementary Figs 9 and 10). To minimize the impact of time-dependent sampling error on the results we subsampled meteorological variables randomly, selecting 45 reports for each 5° grid cell in each calendar season (January–March, April–June, July–September and October–December). To minimize the impact of changes in observational practices on the results we selected only reports with bucket measurements of SST and with Beaufort estimates of wind speed that were converted to wind speed by using the Lindau equivalent scale. If during the previous decades there were not enough reports meeting these requirements, information on anemometer heights of marine carriers was used for the adjustment of wind speed to a standard height, and neutral stability and non-bucket SST measurements were corrected. Atmospheric humidity data are more poorly sampled than the other variables, and temporal sampling inhomogeneity for humidity is much stronger than for the other parameters. To ensure homogeneity of surface turbulent heat flux estimates, instead of using actual humidity data we developed a simple multivariable regression procedure for the reconstruction of relative humidity using temperature, sea level pressure and wind speed data. The procedure was developed with the data for the period 1960–1980 (the best-sampled period for the North Atlantic), and the derived regression model was applied for the reconstruction of relative humidity for the whole period from 1880 to 2007. Use of the reconstructed humidity may result in a random error in latent heat flux estimates of about 5–6 W m$^{-2}$ for monthly values (Supplementary Figs 11 and 12). Reconstruction of the humidity resulted in a close correlation of the latent and sensible heat fluxes, so that we show here the results for the total (sensible plus latent) turbulent heat flux. Subsampled meteorological variables were used to compute sensible and latent heat flux estimates by using a simplified version of the COARE-3.0 algorithm, with parts of the scheme requiring additional parameters being neglected. Subsampling procedures were repeated 20 times for each 5° grid cell and for each calendar season. For every subsample a statistical distribution of the computed fluxes was then approximated by the modified Fisher–Tippet distribution, which was integrated to obtain seasonal mean flux estimates. The average over 20 simulations of the random subsampling provided seasonal estimates of surface sensible and latent heat fluxes for a grid cell. We believe that this procedure produces North Atlantic surface turbulent heat flux time series that are homogeneous in terms of sampling and observational practices. To investigate the impact of the number of samples on the results, we repeated calculations for different numbers of samples from 20 to 70 per 5° grid cell per season. Supplementary Fig. 10b, c shows the robustness of the results to the number of samples. For some regions in the late nineteenth century and the first half of the twentieth century the number of observations was nevertheless very small for deriving the values of surface heat fluxes. For these locations heat flux anomalies were produced by an interpolation procedure (Supplementary Fig. 14 and caption to Supplementary Fig. 5). Comparison of the reconstructed turbulent heat fluxes with the other advanced surface heat flux data sets for the past few decades shows that our fluxes are generally smaller by about 10–30%, although their interannual variability is quite comparable (Supplementary Fig. 15).

Statistical methods. Decomposition of 128-year time series of SST and surface fluxes into long-term (interdecadal) and short-term (interannual) components was performed by applying an 11-year running mean for a running mean over different smoothing windows, for example Fig. 4). The running mean was considered to be the long-term component, and deviations from it were considered to be the short-term component. More sophisticated filtering procedures based on different low-pass and high-pass filters including Lanczos filtering were also applied, with very similar results. However, these procedures result typically in a much larger time series cutoff—that is, data loss—of time series compared with the running mean. Thus, all analyses shown here were performed with running-mean filtering.

Because we focused here on interdecadal and interannual variability and not on secular signals, the time series of both SST and surface turbulent fluxes were detrended by removing the linear trends, estimated with the least-squares procedure. An alternative method to account for secular changes potentially driven by externally forced climate change was to compute an AMV SST index from SST by first subtracting (spatially varying) SST variations that were linearly related to global mean surface temperature. Although differences exist between the two indices, our key findings remain unchanged (Supplementary Figs 6 and 8). The correlation analysis was performed for the detrended time series. The significance of correlation for long-term and short-term components was estimated by taking into account autocorrelation of the time series with the non-parametric test based on phase-scrambling bootstrapping in the frequency domain.

Cross-spectral analysis was performed with the maximum-entropy method based on predicting the available data to infinite time by an autoregressive fitting. An advantage of this method is that it is applicable to short time series when oscillations with two or three periods per record should be identified. The results of the spectral analysis are practically insensitive to the order of the autoregressive model, implying the robustness of estimates of spectral peaks, coherence and phase (Supplementary Fig. 13). Estimates of field significance of correlation patterns were performed from the binomial distribution for the area of the mid-latitude North Atlantic from 35° N to 50° N. 


