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North Atlantic Oscillation impact on tropical north Atlantic winter atmospheric variability

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Abstract. The dominant mode of windspeed variability in the wintertime tropical north Atlantic (TNA) is represented by the North Atlantic Oscillation (NAO). For the December-January-February (DJF) season the leading principal component of TNA windspeed (representing 46% of the total variance) exhibits a 0.68 correlation with the NAO time-series. We show that the NAO impact on TNA trade winds peaks in January and is statistically significant at the 99% level for each month from November through to April. This association arises through the meridional pressure gradient equatorward of the Azores high pressure covarying with the NAO. We also show that the winter NAO index determines monthly precipitation levels across the northern Caribbean throughout the following year. We suggest this rainfall impact is due to long lasting, DJF forced perturbations to the north Atlantic sea surface temperature tripole characteristic of the NAO signal.

Introduction

The main mode of winter atmospheric interannual variability over the north Atlantic is characterised by the North Atlantic Oscillation (NAO) [*Walker and Bliss*, 1932; *Van Loon and Rogers*, 1978; *Rogers*, 1985]. The NAO's strength and sign may be defined as the normalised sea-level pressure difference between the Azores and Iceland [*Jones et al.*, 1997]. Since the NAO is proportional to the meridional surface pressure gradient in this sector it is associated with changes in the strength and direction of winter surface westerly winds over the north Atlantic and northwest Europe [*Bjerknes*, 1964; *Hurrell*, 1995].

The existence of a potential NOA link to the tropical north Atlantic (TNA) has been noted for sometime. The early analysis of [*Bjerknes*, 1961] pointed out that an increase in the magnitude of mid-latitude westerlies was associated with an apparent increase in the TNA trade winds, thus suggesting an NAO connection to the winter TNA. Recent modeling studies [*Visbeck et al.*, 1998; *Sutton et al.*, 2000; *Chang et al.*, 2000] also suggest that fluctuations in the winter TNA trades are correlated with fluctuations in the higher latitude westerlies and might be viewed as a low latitude manifestation of the NAO. The observed significant correlation between the winter NAO and annual Caribbean rainfall [*Malmgren et al.*, 1998] is also suggestive of a link via variability in the local trade wind strength. Despite this growing list of evidence, no study has yet quantified the NAO-TNA trade wind link in terms of its physical basis, its strength, and its time evolution. This paper examines this quantification using standard statistical techniques.

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Data and Methodology

Data are obtained from the NCEP/NCAR global reanalysis project [*Kalnay et al.*, 1996]. Monthly averages of mean sea level pressure (MSLP) and surface wind velocity are obtained for the period 1948-1999. Data are interpolated onto a standard 2.5° x 2.5° grid. Observational indices for the NAO are obtained from the Climatic Research Unit, at the University of East Anglia [*Jones et al.*, 1997], as are the global monthly 0.5° lat-lon gridded precipitation data [*New et al.*, 2000]. Monthly SST fields originate from the 1° × 1° GISST dataset [*Rayner et al.*, 1996].

Spatial correlation analysis is employed to highlight relationships between the NAO and spatial north Atlantic wind fields. Principal component analysis (PCA) [*Kutzbach*, 1967] is used to extract the main modes of windspeed variance in the north Atlantic and to quantify their link to the NAO. Two regions of study are defined as: the north Atlantic (NA) region 0°N-70°N, 65°W-20°E and the tropical north Atlantic (TNA) region 0°N-30°N, 65°W-20°E.

Results

Figure 1 shows the spatial correlation between the NAO and NA windspeeds for the months November through to April. These are the months when the NAO explains most of the NA sea level pressure variance [*Van Loon and Rogers*, 1978]. The well known relationship between enhanced (decreased) mid-latitude westerlies and the positive (negative) NAO phase [*Hurrell*, 1995] is visible at the 99% level of statistical significance. The signal maximises during the winter months, and diminishes with the approach of spring. The plots also reveal a correlation of similar extent and significance in the tropics, showing that a relationship exists between the NAO and the magnitude of the trade winds. The pattern expands zonally out from the northwest African coast and also equatorward from its initial belt at 20°N-30°N. It reaches its maximum areal extent in January before waning through to April. The northern part of the trade wind belt is linked most strongly to the NAO; correlations equatorward of 10°N-15°N are not statistically significant at the 95% level. Figure 1 suggests there is a strong and persistent association between the NAO and winter TNA trade winds.

Correlation of the NAO with the meridional gradient of mean sea level pressure (MSLP), reveals statistically significant patterns similar in location and extent to those in Figure 1 (not shown). These are consistent with geostrophic balance. The sign of the MSLP correlation alternates either

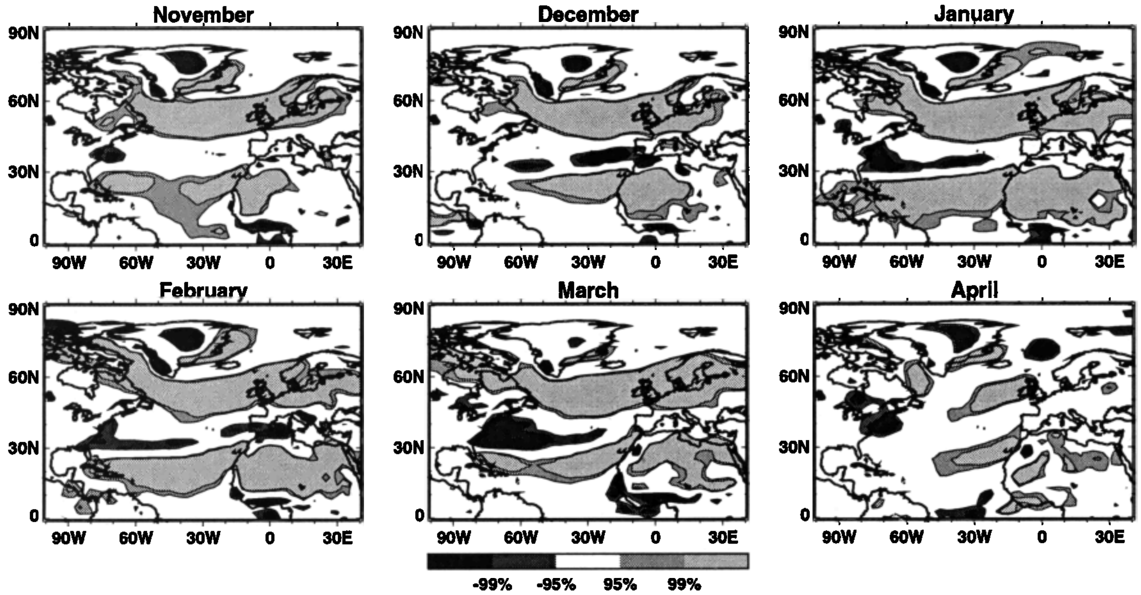


Figure 1. November to April monthly spatial linear correlation of the NAO index against surface windspeed 1948-1999 over the north Atlantic basin. Grayscale shading denotes the regions where the correlation is either positive or negative and statistically significant at the 95% and 99% levels.

side of the Icelandic low and Azores high pressure systems. This indicates that the trade wind anomalies are associated with NAO-linked variations in the strength of the Azores high pressure system. These variations enhance and decrease the meridional pressure gradient on the subtropical high's equatorward side causing strengthening and weakening of the trade winds. Variability in the low pressure equatorial intertropical convergence zone contributes little to the changes shown.

In order to quantify the winter NAO impact on Atlantic trade winds, PCA of surface windspeeds is performed on both the NA and TNA regions. The first EOF for the December-January-February (DJF) season windspeeds for NA is shown in Figure 2(a). The value at each point represents the correlation between the timeseries of PC1 and the windspeed anomalies [*Wallace et al.*, 1992]. The NA plot reveals the covariance of the southern and northern wind bands indicated in Figure 1. This mode represents 34.6% of the total DJF windspeed variance in the north Atlantic. The correlation between the PC1 for NA and the NAO is 0.87 (significant at the 99% level). The normalised timeseries for the two fields are shown in Figure 2(c) (left panel). These confirm that the high correlation is present in all decades except the 1950s. The weaker link in the 1950s may simply reflect errors in the reanalysis fields, due to increased uncertainties in the assimilation of data prior to 1958 [*Kistler et al.*, 2000]. Considering the tropical north Atlantic (TNA) in isolation reveals that the first EOF has the same spatial pattern (Figure 2(b)) as the PC1 for the whole NA sector, and that it represents 45.5% of the total DJF TNA windspeed variance. The correlation between the PC1 for TNA and the NAO is 0.68 (significant at the 99% level). The normalised time series for these fields are displayed in Figure 2(c) (right panel). These results reinforce the hypothesis that the NAO is linked to variability in the north Atlantic trade winds.

To investigate the time dependence of the NAO impact on TNA trade winds, we repeated the PCA for each month

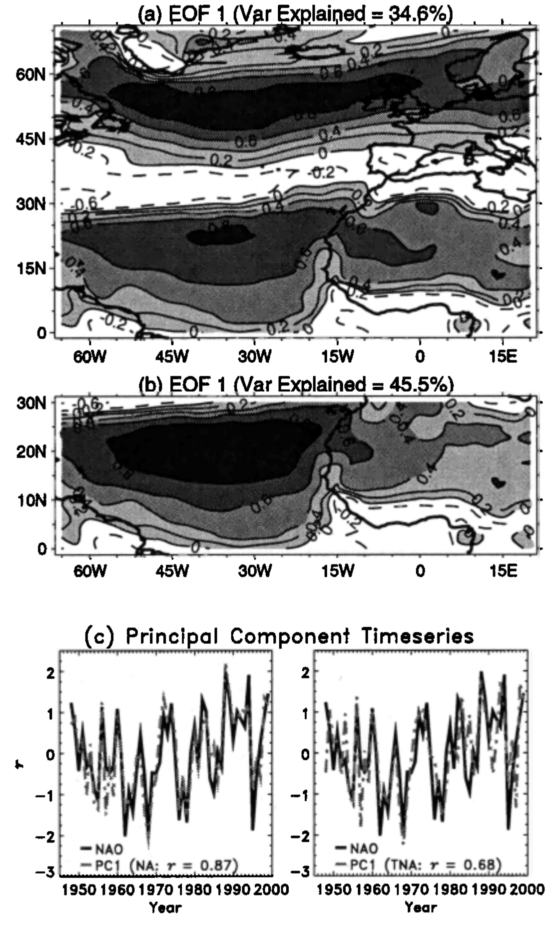


Figure 2. Principal component analysis of (a) north Atlantic (NA) surface windspeed, and (b) tropical north Atlantic (TNA) surface windspeed for the December-January-February seasons 1948-1999. The time series of the first EOFs from (a) and (b) are compared against the NAO in (c).

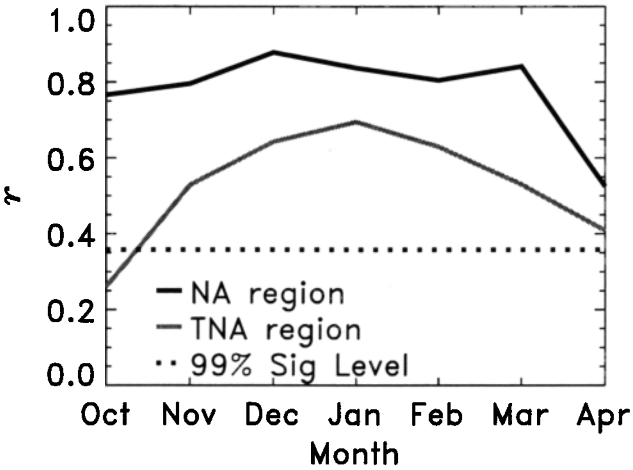


Figure 3. Monthly timeseries of the NAO correlation with the north Atlantic (NA) and tropical north Atlantic (TNA) first EOFs of windspeed. The 99% significance level is shown dotted.

from October to April for both the NA and TNA regions, and obtained correlations against the monthly NAO. Figure 3 shows the time series of these correlations for both regions for the leading PCA. Strongest correlations occur in mid-winter. The NA timeseries shows statistical significance at the 99% level for the whole 7-month period, while the TNA timeseries is only below the said level in October. The months of maximum influence mirror the variability in NAO intensity. It should be noted that although the NAO exhibits seasonal variation, being strongest in boreal winter, its signal persists year-round and is often robust in spring and summer [*Barnston and Livezey*, 1987; *Rogers*, 1990]. Extending our analysis to boreal summer reveals evidence for weak contemporaneous NAO forcing of summer TNA windspeed variability (not shown).

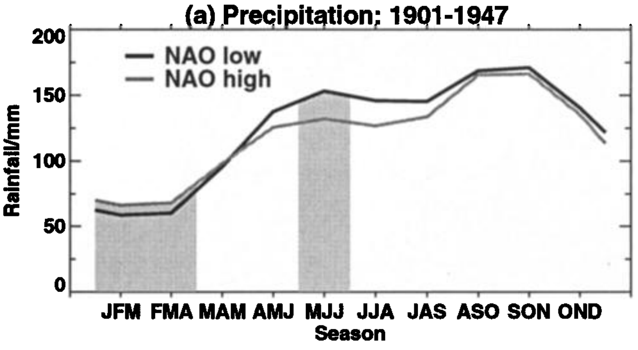
To better quantify the NAO impact on TNA trade wind intensity we divided the DJF NAO timeseries 1948-1999 into composite thirds, representing the 33% lowest NAO years, 33% neutral NAO years, and the 33% highest NAO years. Considering the central TNA region 15°N-25°N, 30°W-60°W, the surface windspeed averages for the three composites are 5.31, 5.93 and 6.33 ms^{-1} respectively. The DJF surface tradewind speed is thus 19% higher for the highest NAO composite years compared to the lowest NAO composite years. The same compositing reveals little change in surface tradewind direction between the highest and lowest NAO composite years. The extent of the NAO influence is seen to be significant throughout the vertical structure of the Atlantic low latitude troposphere. During high NAO years the bifurcation of the subtropical and polar jet streams becomes more defined in the longitudinal region of interest (30°W-60°W). This leads to weakening of the westerly upper level winds in the intermediate region between the jet streams. The weakening from low to high NAO composite years is 30% at 200mb.

The preceding analysis reveals that the influence of the winter NAO on tropical surface windspeeds extends both eastward into North Africa, and westward into the Caribbean. The impact on Caribbean circulation may be linked to the previously published inverse empirical relationship between wintertime NAO and the subsequent annual Caribbean rainfall [*Malmgren et al.*, 1998]. We investigate this relationship further by analysing monthly precipitation data for the Caribbean region 15°N-25°N,60°W-85°W. This area is chosen for its near continuous data record extending back almost a century. The data are split into two independent datasets (1901 to 1947, and 1948 to 1995), to assist the identification of stable NAO/rainfall relationships.

Three monthly area rainfall averages are calculated for the high DJF NAO and low DJF NAO composite third years (as defined in the previous section). Figure 4 shows the difference in annual precipitation between the two NAO regimes for both temporal periods. The results show an above average Caribbean precipitation through to the March of high winter NAO years, followed by below average rainfall after April (the latter in accordance with the previously observed annual inverse relationship). The NAO influence tends to weaken in later months. The seasons where the difference in rainfall between the high and low NAO composite years is statistically significant at the 90% level, based on a Wilcoxon-Mann-Whitney test, are shown shaded. There are 3 and 6 such 3-month seasons for the 1901-1947 and 1948-1995 periods respectively.

Analysis of NAO-composited Caribbean rainfall based on contemporaneous, rather than lagged, NAO indices reveals insignificant differences with NAO sign. Thus the important NAO influence on annual Caribbean precipitation occurs in the preceding winter. Associated research [also see *Hamilton et al.*, 2000] reveals that the wintertime NAO is correlated with spring and early summer sea surface temperature (SST) anomalies in the TNA and Atlantic mid-latitudes. Thus a positive NAO leads to stronger trade winds, to enhanced wind-induced latent heat flux, to TNA SST cooling, and to lower TNA atmospheric moisture content. The

(a) Precipitation: 1901-1947



(b) Precipitation: 1948-1995

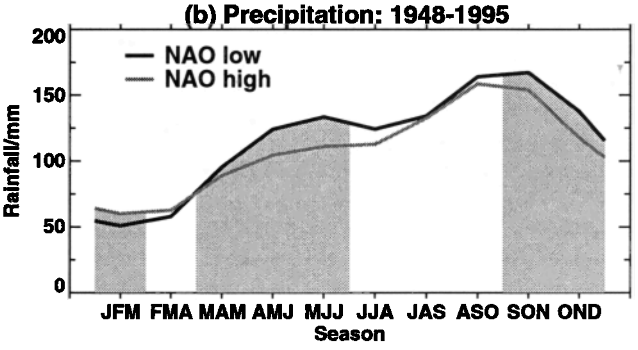


Figure 4. Three monthly seasonal rainfall totals in years with low and high preceding DJF NAO index values during (a) 1901-1947 and (b) 1948-1995. Shading indicates the seasons where the difference in rainfall between the low and high NAO composite years is significant at the 90% level or above.

opposite happens in mid-latitudes. The SST anomalies in both regions are long lasting. The switch in high NAO years from an initial increase in Caribbean precipitation to the annual dominant spring decrease can be explained by a shift in the wind direction impacting the northern Caribbean. Initially the mean flow comes from the northeast originating over the NAO-related warm mid-latitude anomaly. Thus the northern Caribbean receives increased moisture and rainfall. From spring onwards the wind direction becomes more easterly originating over the TNA. With reduced evaporation over the cool TNA SST anomaly, the Caribbean experiences reduced rainfall.

Conclusion

We have shown that the dominant mode of winter windspeed variability in the tropical north Atlantic is characterised by the North Atlantic Oscillation (NAO). The NAO is linked to changes in the strength of the Atlantic subtropical high pressure system which peaks in December-January-February. This influence, in turn, impacts the meridional pressure gradient equatorward of the sub-tropical high, which affects the magnitude of the tropical trade winds. The zone of winter NAO influence on Atlantic trade winds extends from north Africa westward to the Caribbean. We demonstrate that the wintertime NAO affects the following years Caribbean precipitation, and suggest that this forcing is a result of SST anomalies set up by the winter trade winds. A practical application of this work would be the development of a seasonal precipitation forecast model for the Caribbean.

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