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Seasonal predictability of the winter NAO from north Atlantic sea surface temperatures

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[1] We examine the seasonal predictability of the winter (December–January–February) North Atlantic Oscillation (NAO) from lagged north Atlantic sea surface temperatures (SSTs) for the period 1950/1–2000/1. We identify two lagged modes of SST variability whose principal components (PCs) are correlated significantly to upcoming winter NAO indices. We use linear regression with the PCs as predictors to assess the predictability of the winter NAO from cross-validation over the full period and from replicated real-time forecasts over the recent 15 year period 1986/7–2000/1. The model anticipates, in early November, the upcoming winter NAO - for a range of NAO indices - with a correlation between 0.47 and 0.63 for 1950/1–2000/1, and between 0.51 and 0.65 for the replicated real-time forecast period. The model also anticipates the correct NAO sign in 67% to 75% of the last 51 winters and in 80% to 93% of the last 15 winters. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 1620 Global Change: Climate dynamics (3309). **Citation:** Saunders, M. A., and B. Qian, Seasonal predictability of the winter NAO from north Atlantic sea surface temperatures, *Geophys. Res. Lett.*, *29*(22), 2049, doi:10.1029/2002GL014952, 2002.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is the dominant mode of boreal winter atmospheric variability over the north Atlantic [*Walker and Bliss*, 1932; *van Loon and Rogers*, 1978; *Barnston and Livezey*, 1987; *Marshall et al.*, 2001]. The NAO is characterized by a dipole oscillation in sea level pressure between the north Atlantic's subpolar (Icelandic) low pressure and subtropical (Azores) high pressure regions. Year-to-year changes in the strength and sign of the winter NAO are linked to interannual variability in wintertime temperature, precipitation and storminess over the whole north Atlantic sector, with correlations exceeding 0.7 ($p < 0.001$; 1950–2000) at certain locations [*Hurrell*, 1995; *Marshall et al.*, 2001; *Trigo et al.*, 2002]. Skilful NAO seasonal forecasts may bring socio-economic benefits by forewarning of winter climate anomalies and their impacts on business revenue, commerce and society.

[3] Attempts to seasonally predict the wintertime NAO have produced little skill to date. Efforts have focussed on the role of Atlantic SSTs in influencing the NAO and of imparting seasonal predictability. Recent numerical model studies have examined the topic in some detail but little skill has been found. The consensus view of dynamical models is that the ocean influence on the NAO is weak but not negligible (e.g., see the review by *Marshall et al.* [2001]). Observational studies, in contrast, appear more promising for detecting NAO seasonal predictability although quantitative hindcast and/or replicated real-time skill determinations have not been made. *Czaja and Frankignoul* [1999, 2002], using maximum covariance analysis, report that anomalies in the early winter (November–January) NAO are related to prior SST anomalies in the north Atlantic. The signal comes mainly from mid-latitudes but an independent competing forcing is also observed from the equatorial tropical Atlantic. *Drévillon et al.* [2001], using a singular value decomposition analysis, report a significant covariance between a summer north Atlantic SST anomaly and an upcoming winter NAO-like structure.

[4] In this paper we examine the seasonal predictability of the winter (December–January–February) NAO from lagged north Atlantic SSTs for the period 1950/1–2000/1. We achieve this by identifying the SST lagged spatial modes whose principal components are correlated significantly to upcoming winter NAO indices. Hindcasts and replicated real-time forecasts of these NAO indices are then made using standard linear regression.

2. Data

[5] We employ monthly gridded SST and mean sea level pressure (MSLP) data from the NCEP/NCAR global reanalysis project [*Kalnay et al.*, 1996]. These data span the period from 1st January 1950 to 31st October 2000 and cover the north Atlantic sector 0°N– 65°N and 0°W–100°W. We analyze these data on a standard 2.5° × 2.5° latitude/longitude grid. Cells with sea ice occurring in any month of the historical record are excluded from the SST analyses.

[6] We examine the predictability of three different winter NAO indices. 'Winter' refers to the 3-month December–January–February (DJF) period and 'winter NAO' will be referred to henceforth as $\mathrm{NAO_{DJF}}$. The $\mathrm{NAO_{DJF}}$ indices employed are (1) the standardized difference in MSLP between southwest Iceland and Gibraltar [*Jones et al.*, 1997] compiled by the Climatic Research Unit at the University of East Anglia; henceforth the *CRU* NAO_{DJF}*index*. (2) the NAO teleconnection index maintained by the US Climate Prediction Center (CPC) and computed from the rotated principal component analysis of monthly northern hemisphere 700 hPa geopotential heights [*Barnston and Livezey*, 1987]; henceforth the *CPC* NAO_{DJF}*index*. (3) the leading principal component of North Atlantic DJF MSLP

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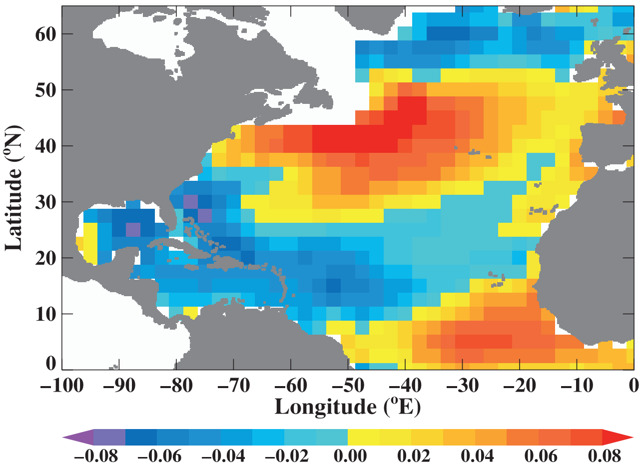
over the same (20°N–70°N, 90°W–40°E) sector employed by *Hurrell* [1995]; henceforth the *MSLP* NAO_{DJF} *index*.

3. Lagged Modes of Atlantic SST Variability

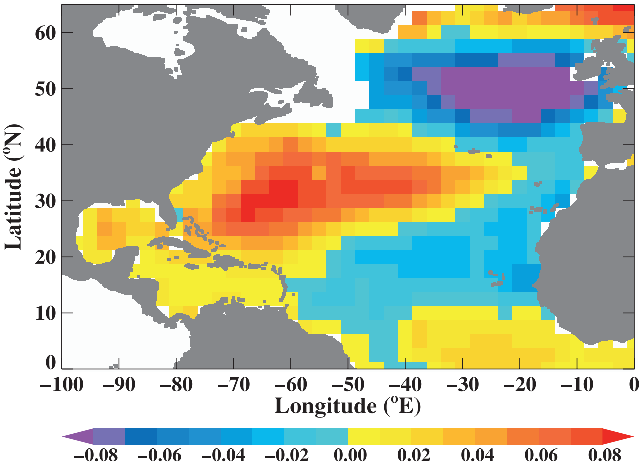
[7] As we are interested in predicting the wintertime NAO before the onset of winter, our study focusses on lagged modes of north Atlantic SST variability through to the end of October. These data would permit an NAO_{DJF} prediction to be issued in early November. We employ principal component analysis (PCA) to extract the leading lagged modes of SST variance over the north Atlantic. Prior to PCA we standardize the SST time series in each grid cell to ensure that all cells have equal importance in the covariance matrix. Standardisation means subtracting the mean and dividing by the standard deviation. Potential NAO-linked modes of SST variability are identified from 1-, 3- and 5-month mean lagged SST anomalies. Averages are defined as follows: 1-month mean refers to October SST anomalies, 3-month mean to August–October average anomalies, and 5-month mean to June–October average anomalies. The ten leading PCs from each lagged averaging period are correlated with the three NAO_{DJF} indices to identify the lagged modes of SST variability linked to the upcoming NAO_{DJF}. For a mode to prove acceptable its time series must have a correlation which is statistically significant and temporally quasi-stable with each NAO_{DJF} index. Statistical significance is defined as a correlation p-value <0.10. Temporal quasi-stability is defined as showing statistical significance over the period 1950/1 to 2000/1 and over the sub-period 1950/1 to 1985/6.

[8] The 3- and 5-month mean SST anomalies over the north Atlantic exhibit two modes - EOF2 and EOF5 - which pass the above criteria. There is no 1-month SST variability mode which passes these criteria. This indicates that SST anomalies averaged over prior multi-month periods are linked more effectively to the forthcoming NAO_{DJF} than are SST anomalies averaged over just the prior 1-month period. We find that modes based on the 5-month mean (hereafter JJASO (June–July–August–September–October) SST anomalies are marginally more significant and stable than the same modes computed from 3-month anomalies. Further checks with 4-month and 6-month mean anomalies also showed the 5-month mean to be best.

[9] Figure 1 shows the two spatial modes of JJASO mean SST variability which are linked significantly and quasi-stably to NAO_{DJF}. We denote these modes as SST_{JJASO} EOF2 and SST_{JJASO} EOF5. Red/blue indicates that warm/cold SST anomalies are linked to positive NAO_{DJF}. The EOF2 pattern is associated with warm SST anomalies to the southeast of Newfoundland and within 10° of the equator, and with cold SST anomalies over the southwest north Atlantic and Caribbean Sea and to the northwest of the UK. The corresponding time series, PC2, explains 11.5% of the total variance and has correlations 1950/1–2000/1 with the *CRU*, *CPC* and *MSLP* NAO_{DJF} indices of 0.43, 0.48 and 0.61 respectively (all significant below 0.005 after correction for autocorrelation). The EOF5 pattern exhibits mainly a contrast between warm SST anomalies off the US eastern seaboard and cold SST anomalies to the west of the UK. PC5 explains 6.5% of the total variance and has correlations 1950/1–2000/1 with the *CRU*, *CPC* and *MSLP* NAO_{DJF} indices of 0.38, 0.32 and 0.36 respectively (all significant below 0.02 after correction for autocorrelation). The leading mode of SST_{JJASO} variability, EOF1, explains 36.3% of the total SST variance but is not related to the forthcoming NAO_{DJF}.



(a) NAO_{DJF} Predictor Mode 1: SST_{JJASO} EOF 2



(b) NAO_{DJF} Predictor Mode 2: SST_{JJASO} EOF 5

Figure 1. The two orthogonal spatial modes, (a) EOF2 and (b) EOF5, of north Atlantic standardized JJASO mean SST anomalies whose time series are linked significantly and quasi-stably to upcoming NAO_{DJF} indices. The modes are shown for the period 1950–2000. The colour bar shows the sign and normalised strength of the spatial pattern.

4. Prediction Skill for NAO_{DJF} Indices

[10] The two orthogonal SST PCs identified in section 3 are easily incorporated as predictors into linear regression models to assess the seasonal predictability of NAO_{DJF} from north Atlantic SSTs. Being uncorrelated the two PCs combine to strengthen the NAO predictability. We assess the predictability in two ways: from cross-validated hindcasts for the period 1950/1–2000/1 and from replicated real-time forecasts for the recent 15 year period 1986/7–2000/1.

[11] Our cross-validation design is standard [*Michaelsen*, 1987]. Each of the 51 years from 1950/1 to 2000/1 is withdrawn in turn, and a regression model is built using

SST_{JJASO} PC2 and PC5 from the remaining 50 years to make a hindcast for the NAO_{DJF} of the withdrawn year. The 51 hindcasts are compared with the 51 observations to compute the prediction skill. While cross-validation provides a good estimate of the true forecast skill in large samples as here [e.g., *Wilks*, 1995], it is desirable for unbiased estimates of true skill to employ replicated real-time forecasts in which training and forecast periods are firmly separate. Our replicated real-time forecast scheme uses an initial training period from 1st June 1950 to 31st October 1985, leaving the 15 winters 1986/7–2000/1 for model forecast assessment. The training period increases one year at a time as each forecast is made - an updating procedure which replicates the operation of a real-time forecast. The prediction models for the three different NAO indices are trained separately. The prediction skill is computed by comparing the 15 independent forecasts with the 15 observed NAO_{DJF} values. While this skill is the true forecast skill for the 15-year period, it may not be representative of the true skill over longer periods.

[12] Several methods are in common use to assess the deterministic skill of forecast models [e.g., *Wilks*, 1995]. We employ the correlation (r) between forecast and observed NAO indices, the percentage of variance explained (PVE), and the percentage improvement in root mean square error over a climatological forecast ($RMSE_{cl}$). Climatology is taken as the running 5-year mean prior to each forecast year in order to minimize inflation of $RMSE_{cl}$ caused by decadal trends in NAO_{DJF}. Using a fixed 1961–1990 climatology produces similar $RMSE_{cl}$ skills for the 51-year cross-validated period but higher skills for the replicated real-time 15-year forecast period. We compute the statistical significance of the correlation and PVE skills by randomly selecting (with replacement) 2000 sets of predicted and observed NAO_{DJF} values from the original 51 (15) NAO_{DJF} predicted and observed values over the cross-validation period (replicated real-time forecast period). The skill from each random set is calculated for each skill measure and the results histogrammed to compute the probability of exceeding the original skill level by random chance.

[13] Our model's predictive skill for NAO_{DJF} from north Atlantic SSTs is shown in Table 1. Similar predictive skill is found for each index although the MSLP and CPC NAO indices characterizing the large-scale NAO signal show higher skill than the CRU NAO index based on the normalized pressure difference at two fixed stations. Using SST data through the end of October the model anticipates the upcoming winter NAO - for a range of NAO indices - with a correlation between 0.47 and 0.63 for the 1950/1–2000/1 cross-validated period, and between 0.51 and 0.65 for the 1986/7 2000/1 replicated real-time forecast period. The model anticipates between 22% and 40% of the NAO_{DJF} variance from cross-validation and between 26% and 41% from replicated real-time forecasts. The model offers around a 20% improvement in RMSE over a prior 5-year climatology forecast. Finally, the model anticipates the correct NAO_{DJF} sign in 67% to 75% of the 51 cross-validated forecast winters and in 80% to 93% of the 15 replicated real-time forecast winters. The predictive skills computed over the cross-validation and replicated real-time forecast periods are all significant with p-values <0.0005 and <0.01 respectively. Using *Barnston and Ropelewski*'s [1992] interpretation for the value or utility of a forecast based on its correlation skill, our NAO_{DJF} skill levels are 'marginal but useable'.

Table 1. Predictive Skill of Winter (DJF) NAO Indices from Prior JJASO North Atlantic SST Anomalies

	Cross-Validation Skill 1950/1–2000/1			Replicated Real-Time Forecast Skill 1986/7–2000/1		
NAO_{DJF} Index	r	PVE (%)	$RMSE_{cl}$ (%)	r	PVE (%)	$RMSE_{cl}$ (%)
CRU	0.47 (0.11)	22 (−4)	21 (9)	0.51	26	24
CPC	0.52 (0.25)	27 (4)	19 (11)	0.65	41	28
MSLP	0.63 (0.54)	40 (28)	18 (11)	0.57	30	19

Brackets indicate the cross-validated skill from multi-decadal SST variability and trends.

[14] Table 1 also shows how much of the NAO_{DJF} seasonal predictive skill arises from trends and multi-decadal variability in north Atlantic SSTs rather than from interannual SST variability. The bracketed numbers show the cross-validated skill obtained using running 9-year averages of the SST PC2 and PC5 time series (similar results are obtained with running 5-, 7-, 11-, and 13-year averages). These numbers show that the skill contribution from SST long-term trends and decadal-scale variability varies with NAO index and with skill measure. In general, multi-decadal variability contributes the minority of the CRU and CPC NAO_{DJF} seasonal skills but the majority of the MSLP NAO_{DJF} seasonal skill. The latter is due to a higher fraction of the MSLP NAO_{DJF} variance being explained by long-term variability.

5. Discussion

[15] The seasonal predictive skill for NAO_{DJF} deduced herein appears to exceed that estimated by *Czaja and Frankignoul* [2002] for early winter (November–January) NAO. It is also, to our knowledge, the highest skill yet found for the winter (DJF) NAO.

[16] The physical explanation for the winter NAO predictability appears linked, at least partly, to the persistence of north Atlantic SST anomalies from summer/autumn through to winter. This SST persistence facilitates the creation of the SST tripole pattern linked contemporaneously to NAO_{DJF} [e.g., *Rodwell et al.*, 1999]. While this explanation points to positive feedback between SSTs and the NAO, our study can not rule out the influence of another factor which forces both the SST and the NAO. The SST persistence is illustrated in Figure 2. (Figure 2a) shows the correlation pattern 1950/1–2000/1 of north Atlantic SST_{JJASO} against the coming winter CRU NAO_{DJF} index. This pattern, with a positive correlation center to the southeast of Newfoundland encircled on three sides by negative correlation areas, resembles the 'North Atlantic Horseshoe' feature identified by *Czaja and Frankignoul* [2002] and linked to the November–January NAO. 15% and 7% of the 621 grid cells in (Figure 2a) have correlation significances <0.05 and <0.01 respectively. (Figure 2b) shows the correlation pattern 1950/1–2000/1 between the CRU NAO_{DJF} index and the contemporaneous north Atlantic SST_{DJF} field. This reveals the familiar NAO/SST tripole pattern, noted above, with a positive correlation center

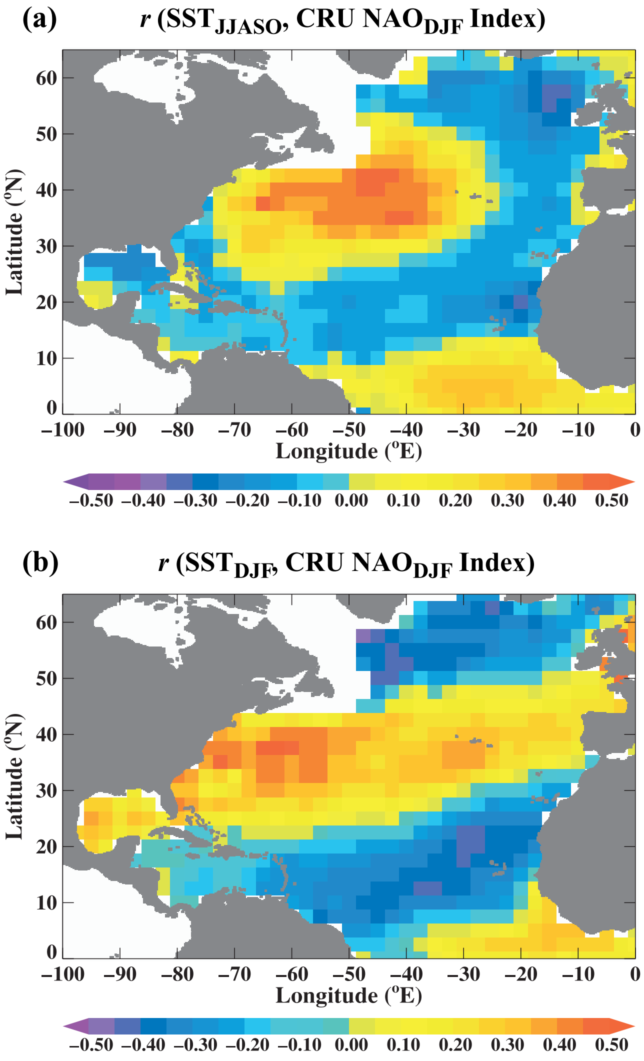


Figure 2. The correlation patterns of north Atlantic (a) SST$_{JJASO}$ and (b) SST$_{DJF}$ anomalies with the CRU NAO$_{DJF}$ index for the period 1950/1–2000/1. Correlation values of 0.28, 0.36 and 0.45 are significant respectively at the levels 0.05, 0.01 and 0.001.

to the south of Newfoundland and off the US eastern seaboard, and two negative correlation centers located between Greenland and the UK and over the tropical north Atlantic. 38% and 15% of the grid cells in (Figure 2b) have correlation significances <0.05 and <0.01 respectively. Comparison of (Figures 2a and 2b) shows a clear similarity in pattern. The pattern correlation between the Figures is 0.56. This pattern correlation arises due to persistence of SST anomalies from JJASO to DJF.

[17] Although the NAO$_{DJF}$ seasonal skill appears marginal but useable, two notes of caution are appropriate. First, the skill exhibits decadal-scale variability. A running 10-year correlation between our model cross-validated hindcasts and observations for each NAO index (not shown) shows that skill is lower in the 1960s and 1980s, and higher in the 1970s and 1990s. The reason(s) for these decadal changes in the strength of the SST$_{JJASO}$ relation to NAO$_{DJF}$ is unclear. Examining their cause will form an important topic for further study. The second caution concerns the shortness of the 51-year test period. It is important to examine the stability of the method over a longer period of time.

6. Conclusions

[18] We have identified marginal but useable skill ($r \sim 0.5$ to 0.6) in predicting the winter (DJF) NAO by early November for the period 1950/1–2000/1. The skill comes from north Atlantic SST anomalies averaged over several prior months. The NAO$_{DJF}$ link to these lagged SSTs is strongest for the 5-month JJASO period, but 3-month ASO SSTs are also useable. Our predictors are two lagged orthogonal PCs of SST$_{JJASO}$ variability which are linked significantly and quasi-stably to upcoming NAO$_{DJF}$ indices. The NAO$_{DJF}$ predictability appears linked to the persistence of SST anomaly patterns from summer through to winter which then feedback to influence the NAO through the known NAO/SST tripole association. However, the reason(s) why these anomalies persist better in certain years and decades than in others is unclear and requires further investigation.

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