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Decadal variability of the NAO: Introducing an augmented NAO index

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[1] The wintertime NAO is traditionally defined as the first Empirical Orthogonal Function of monthly sea level pressure (SLP) anomalies for all winters and therefore remains fixed in space. The associated NAO index represents the projection of SLP onto the fixed NAO pattern. The NAO index is positive when the pressure contrast between the two centers of action is particularly strong; it is negative when the contrast is weak. This index represents an incomplete description of the wintertime NAO as the pattern is found to shift location on decadal timescales. This study investigates the movement of the centers of action (or nodes) of the NAO for winter in 20-yr running windows starting in 1871. A new climate index, the Angle index, is introduced. It is a measure of the asymmetry in location of the two nodes of the NAO defined in the partially overlapping 20-yr windows. The Angle index has a value of zero only when both nodes are located on the same meridian. It increases in positive value as the curve connecting the nodes tilts more to the northeast; it becomes negative when the tilt is to the northwest. The Angle index complements the smooth NAO index, which is the traditional NAO index averaged over the 20-yr window, especially when the Angle index is strongly negative as occurred during the Arctic warming of the early to mid 20th century. Regression analysis shows that the Angle index provides additional information about climate variability beyond that provided by the smooth NAO index. **Citation:** Wang, Y.-H., G. Magnusdottir, H. Stern, X. Tian, and Y. Yu (2012), Decadal variability of the NAO: Introducing an augmented NAO index, *Geophys. Res. Lett.*, 39, L21702, doi:10.1029/2012GL053413.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is the dominant pattern of climate variability in the Northern Hemisphere winter, influencing weather and climate in the North Atlantic and surrounding areas. The NAO is characterized by a seesaw structure in sea level pressure (SLP) anomalies of the subpolar low and the subtropical high [e.g., Hurrell, 1995]. The change in pressure gradient between high and low latitudes results in an anomalous mid-latitude westerly flow that

is accompanied by anomalous advection of temperature and moisture. When the NAO has positive polarity, the westerly flow is located further northward and becomes stronger. Increased westerlies bring warm and moist maritime air over northern Europe, while increased northerlies over the high-latitude western basin bring both cold, dry air and increased sea-ice flux to the northwest Atlantic [e.g., Vinje, 2001].

[3] The NAO is generally described as a pattern that is spatially fixed in time, however, the NAO has been shown to move on decadal time scales [e.g., Jung *et al.*, 2003]. The northern node of the NAO shifted eastward during 1978–1997 compared to 1958–1977 [e.g., Hilmer and Jung, 2000; Jung and Hilmer, 2001; Wang and Magnusdottir, 2012]. A shift in the NAO influences the spatial pattern in the pressure gradient and therefore changes wind variability associated with the NAO. The spatial pattern of surface climate variables related to the NAO may also be shifted. For instance, when the northern node of the NAO was eastward located during 1978–1997, the NAO-related warm and cold anomalies in high latitudes were also located eastward [Jung *et al.* 2003, Figure 5]. Over the same time period, anomalous northerly winds in the Fram strait (between Greenland and Spitzbergen) lead to increased sea-ice export from the Arctic [Hilmer and Jung, 2000].

[4] The traditionally-defined NAO index refers to a fixed NAO pattern and cannot represent the spatial variability of the NAO in time [e.g., Pinto and Raible, 2012]. When monthly SLP anomalies are projected on this representation of the NAO and suggest a weak signature, it may be that in fact the NAO is strong but shifted in location relative to the long-term average pattern. Here we define a new index complementary to the NAO index on a 20-yr time scale that quantifies the relative location of the two centers of action of the NAO. We examine the relation of this new index, the Angle index, to the NAO index and show that it helps capture climate variability over regions that are sensitive to the shift in the NAO.

2. Data and Methods

[5] We use monthly data from the second version of the Twentieth Century Reanalysis (20CRv2) [Compo *et al.*, 2011], spanning 1871 through 2008 with a $2^\circ \times 2^\circ$ spatial resolution. Wintertime SLP and near-surface (sigma level = 0.995) wind are extracted. The 20CRv2 is constrained by surface pressure observations, using sea surface temperature and sea-ice concentration as boundary conditions for the data assimilation. Climate variability represented by the 20CRv2 is in good agreement with other reanalysis datasets, except for a noticeable bias in temperature near the poles [Compo *et al.*, 2011]. For surface air temperature (SAT) we use a gridded data set (NansenSAT) that is available

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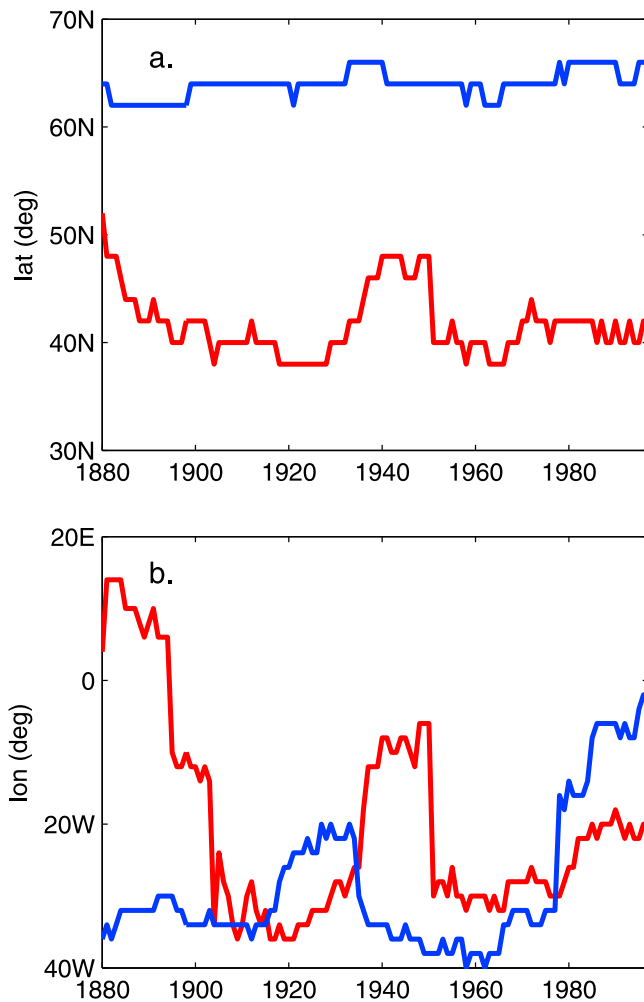


Figure 1. (a) Latitude of the northern node (blue) and the southern node (red) of the NAO in 20-yr windows where neighboring windows have 19 years in common. (b) Longitude of the northern node (blue) and the southern node (red) in the same 20-yr windows. The x-axis in both Figures 1a and 1b shows the 10th year of each 20-yr period.

monthly for 1900 through 2008 at a spatial resolution of 2.5° by 2.5° [Kuzmina *et al.*, 2008].

[6] We identify the slow movement of the NAO pattern by analyzing 20-yr running windows over the entire time period such that each subsequent window is moved over by one year. In this way, two neighboring periods have an overlap of nineteen years. There is a total of 118 such 20-yr periods over the entire record. All 20-yr periods referenced in the figures and text are identified by their 10th year. (For example, December 1871–March 1891 is shown as 1880.) The NAO pattern is defined as the first Empirical Orthogonal Function (EOF1) of monthly SLP anomalies in each 20-yr window over the region $20^\circ\text{--}80^\circ\text{N}$, $90^\circ\text{W--}40^\circ\text{E}$. The monthly SLP anomalies are de-seasonalized by subtracting the 20-yr average for the relevant month. The sign of EOF1 is fixed so that the northern node of the NAO is always negative.

3. Location of the Centers of Action of the NAO

[7] The NAO spatial pattern was computed as EOF1 of SLP in all 118 of the 20-yr time windows spanning the entire

record from 1871 to 2008. We put together an animation of the progression through time (or time windows) of the NAO computed in this fashion (see Animation S1 in the auxiliary material).¹ It reveals a remarkable variability in the spatial pattern of the NAO on the decadal time scale. Both centers of action move in space.

[8] The decadal variability of the spatial pattern of the NAO is further examined in Figure 1, which depicts the location of the two nodes. The northern node is shown in blue, the southern node is shown in red in both panels. Latitude of each node as a function of time period is shown in Figure 1a, longitude is shown in Figure 1b. The northern node mostly shifts in longitude, hovering around 64°N through time. The eastward shift in the northern node from 1958–1977 to 1978–1997, that has been documented using various datasets [e.g., Hilmer and Jung, 2000; Jung *et al.*, 2003], is also revealed using the 20CRv2. The eastward shift in the northern node since the 1970s is more pronounced than the eastward shift in the 1920s. In fact, recent decades show the greatest longitudinal excursion of the northern node of the NAO. This is consistent with the results of Zhang *et al.* [2008] who focused on the movement of the Arctic Oscillation since 1986. The southern node changes location both in longitude and latitude. It was most eastward shifted in the late 19th century. The southern node again shifted eastwards during the mid-20th century, a period during which it was also shifted northward.

4. Two Climate Indices

[9] It is useful to quantify the relative location of the two nodes of the NAO by an index. We identify the angle that the line on the surface of a sphere connecting the two nodes of the NAO makes with the meridian running through the southern node and call it the Angle index. (To consider the influence of the Earth's curvature on angle values, we convert locations of the two nodes in spherical coordinates into Cartesian coordinates of the Mercator projection). When both nodes are located at the same longitude, the Angle index is zero. When the northern node is located to the east of the southern node, the Angle index has a positive value and we say that the NAO has a positive tilt. When the northern node is located to the west of the southern node, the Angle index is negative and we say that the NAO has a negative tilt. As is customary for climate indices it is convenient to normalize the Angle index so that it has a mean of zero and standard deviation of one, shown in blue in Figure 2a. We define the smooth NAO index as the average of the monthly, wintertime NAO indices over each 20-yr window. The monthly NAO index is computed by projecting the monthly SLP field onto the fixed NAO pattern corresponding to EOF1 for the entire time period (1871–2008). The normalized smooth NAO index is shown by the red curve in Figure 2a.

[10] The smooth NAO index and the Angle index (Figure 2a) are highly correlated with a correlation coefficient 0.57, which is significantly different from zero at the .05 level. It implies that when the NAO is in the positive polarity, it is likely to be positively tilted. The scatter plot in Figure 2b shows that when the Angle index is close to zero,

¹Auxiliary materials are available in the HTML. doi:10.1029/2012GL053413.

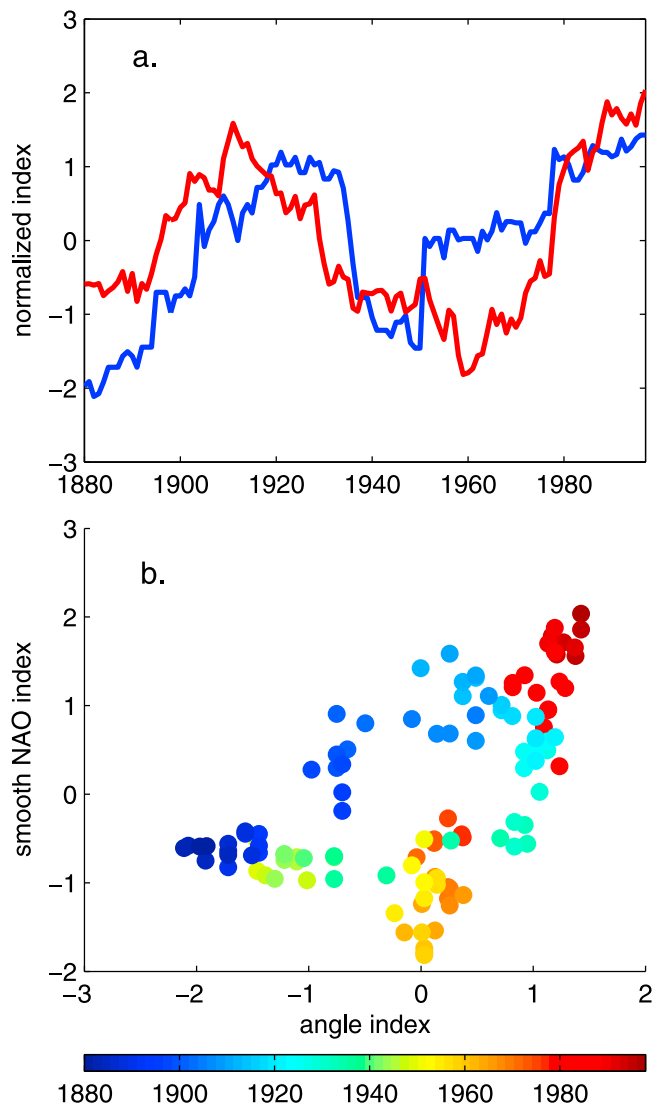


Figure 2. (a) The normalized Angle index (blue), and the normalized smooth NAO index (red). The x-axis shows the 10th year of each 20-yr window. (b) Scatter plot of the normalized Angle index (x-axis) and the normalized smooth NAO index (y-axis) for 20-yr running windows. Colors identify the year corresponding to the 10th year of different 20-yr periods.

the points seem to belong to two distinct regimes of the smooth NAO index. When the normalized Angle index is less than -1 , the range for the corresponding smooth NAO index is small, with values between -0.5 and -1 . This suggests that when the NAO has a substantial negative tilt, the Angle index provides additional information that cannot be provided by the smooth NAO index alone. When the Angle index is greater than -1 the relationship between the two indices is closer to linear but there is still considerable variability in the NAO index values that correspond to a given value of Angle index. Points in the scatter plot are colored according to time (Figure 2b). During the late 19th century, the points are primarily located where the Angle index is smaller than -1.5 . The points appear to progress clockwise in the space made up by the two indices and by the early 1950s return to the quadrant with both negative

Angle and negative smooth NAO index. Since the 1950s, the points are spread between -2 and 0 in smooth NAO index with an Angle index close to zero. After the 1970s, the points appear to cluster where both the Angle index and smooth NAO index are large and positive.

[11] The low-frequency variability in the Angle index reflects the relative movement of the nodes. The Angle index for any one time window implies certain wind variability for that time window since wind variability corresponds to the spatial distribution of pressure anomalies associated with the tilt of the NAO. To investigate this issue we have composited the NAO-associated SLP and near surface wind anomalies corresponding to values of the normalized Angle index greater than one standard deviation and less than one negative standard deviation. NAO-associated anomalies of a field refer to regression analysis between the monthly NAO index (for the winter months) and the field in question. Results are shown in Figure 3a for large positive values and Figure 3b for large negative values of the Angle index. From Figure 3 we see that high values of the Angle index are associated with westerly NAO-associated flow, whereas large negative values of Angle index are associated with more southerly NAO-associated flow over the eastern basin and latitudes 40 – 65°N .

5. Discussion

5.1. The Arctic Warming

[12] Previous studies have focused on the NAO index as providing information on the temporal behavior of the NAO. However, the usual NAO index carries no information on how the NAO changes spatially on decadal time scales. The smooth NAO index augmented by the Angle index may lead to different insights regarding the relationship of the NAO and other climate fluctuations on decadal time scales. For example, the Angle index dropped to very negative values from the late 1930s to the early 1950s (Figure 2a, blue curve). This negative anomaly of the Angle index overlaps with the timing of the so-called Arctic warming, which started in the early 1920s, reached a peak in the 1940s and weakened thereafter [Bengtsson *et al.*, 2004]. Previous research downplays the influence of the NAO on the Arctic warming during the early to mid 20th century because of poor correlation with the NAO [e.g., Bengtsson *et al.*, 2004; Wood and Overland, 2010]. Bengtsson *et al.* [2004] attribute the Arctic warming to the retreat of sea ice, driven by an increase in southwesterly flow towards the Barents Sea. However, they did not demonstrate that a change in the large-scale circulation had taken place.

[13] We computed 20-yr window means of the Arctic SAT anomaly for the partially overlapping windows for two different time intervals: the 20-yr running windows centered in 1915–1925 and the 20-yr running windows centered in 1940–1950 (for a total of eleven 20-yr windows in each time interval). We then computed the mean of the eleven window-means for each period. Let us indicate the respective variables by $\overline{\text{SAT}}_{15-25}$ and $\overline{\text{SAT}}_{40-50}$. These derived Arctic SAT variables are compared to the Angle index below.

[14] As seen in Figure 2a, the Angle index (blue) was positive during the 20-yr running windows centered on 1915–1925. The Angle index plunged to negative values during the 20-yr running windows centered in the later

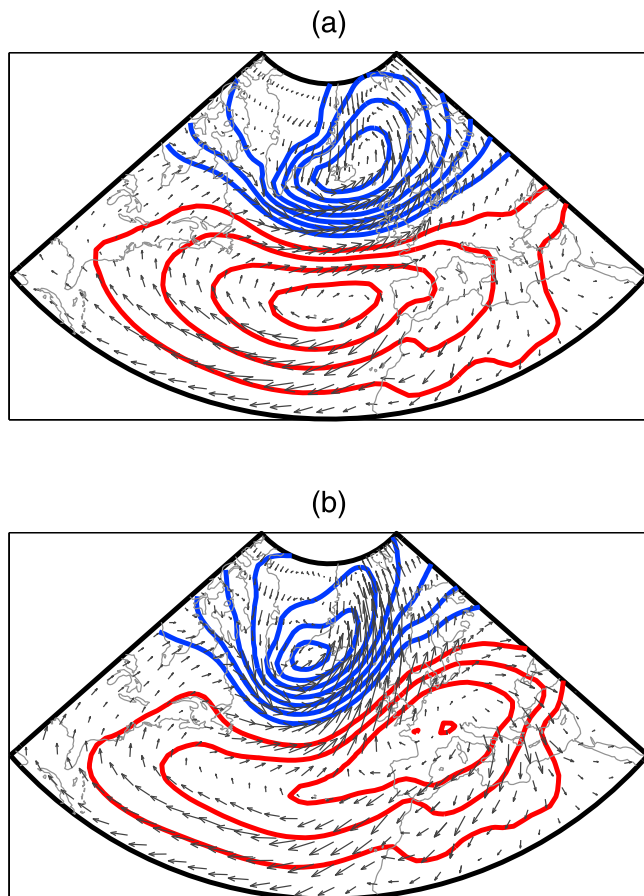


Figure 3. Composite of NAO-associated SLP and near surface wind anomalies corresponding to (a) values of the normalized Angle index greater than one standard deviation above the mean, (b) values of the normalized Angle index less than one standard deviation below the mean. Blue contours show negative and red contours show positive SLP anomalies.

period, a time interval normally associated with the Arctic warming. The negative tilt due to a shift in the southern node (Figure 1b) is a possible cause of the southwesterly NAO-related flow over the North Atlantic (see Figure 3b) and the high-latitude temperature anomaly. The SAT fields give a consistent view. The field of \widehat{SAT}_{15-25} is shown in Figure 4a. A cold anomaly is centered over Spitsbergen in the North Atlantic sector of the Arctic. Figure 4b shows a prominent positive temperature anomaly in \widehat{SAT}_{40-50} that is centered slightly east of Spitsbergen over the Barents Sea. This is consistent with the more southwesterly direction of the NAO-associated flow during this period bringing warmth to the area of the Barents Sea. This is also consistent with the hypothesis presented in Bengtsson *et al.* [2004].

[15] For comparison we also examined the mean SAT anomalies of eleven 20-yr time periods centered in the 1980s and 1990s (not shown). The time periods are characterized by intense Arctic warming, but this warming that has primarily been associated with anthropogenic effects is centered over the high-latitude continental areas with quite small signatures over the Arctic sector of the North Atlantic.

5.2. Regression Models With Different Climate Indices

[16] We use three multiple linear regression models with different predictor sets to evaluate the importance of the two climate indices for predicting the 20-yr running mean of low-level zonal wind. The multiple linear regression models predict zonal wind at each grid point as a function of 1) the smooth NAO index, 2) the Angle index, 3) both indices. We objectively evaluate the importance of the two indices by comparing the coefficients of determination, R^2 , among the linear regression models. The R^2 measures how well a regression model explains the variability in the 20-yr running mean of zonal wind. When the R^2 value is close to 1, the linear regression model explains most of the variability.

[17] When the only predictor is the smooth NAO index (Figure 5a), two zonally extended areas of maximum R^2 are evident, each associated with a center of action of the NAO. R^2 of the model using only the Angle index (Figure 5b)

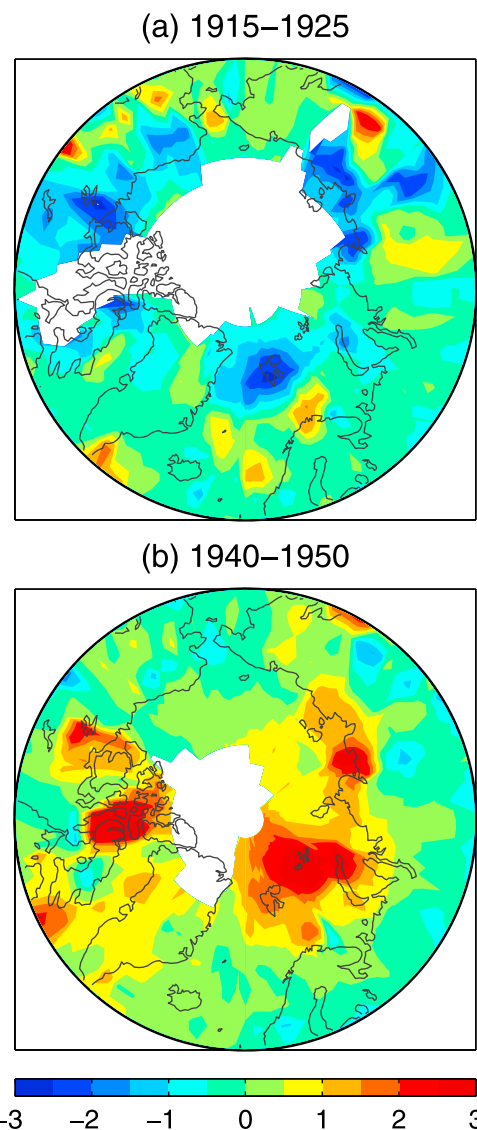


Figure 4. Mean SAT anomalies ($^{\circ}\text{C}$) over eleven 20-yr partially overlapping, consecutive windows centered on (a) 1915 to 1925, (b) 1940 to 1950.

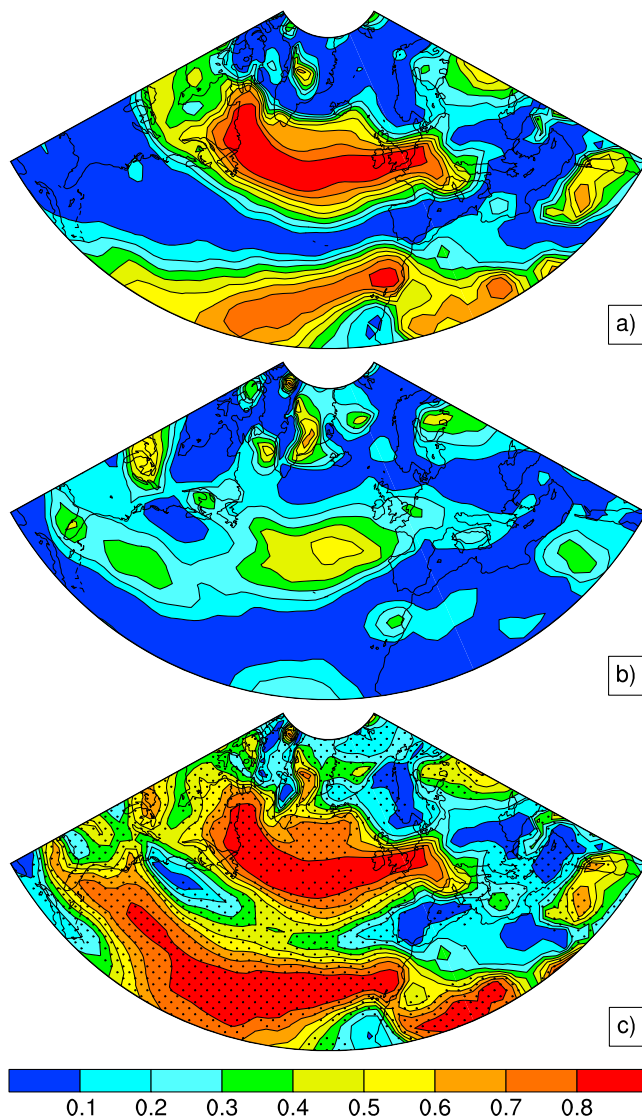


Figure 5. Maps of R^2 for a linear regression model that explains normalized 20-yr mean anomalies of zonal wind using (a) only the smooth NAO index as predictor, (b) only the Angle index, and (c) both the smooth NAO index and the Angle index. Dotted area shows where the Angle index adds information significantly (with p -value ≤ 0.05), given that the smooth NAO index is already in the regression model.

shows an area of modest values crossing the North Atlantic from the southwest, where R^2 in Figure 5a is weak, towards the northeast. A small part of this area overlaps the northern area of maximum R^2 shown in Figure 5a with the remaining portion found between the areas of R^2 maxima in Figure 5a. Thus, the Angle index increases R^2 over some areas where the smooth NAO index has little correlation with the 20-yr running mean zonal wind. The movement of the NAO action centers changes wind variability between the two nodes. It appears that the Angle index, which measures the change in the relative location of the two nodes of the NAO, can

capture the variation in zonal wind at latitudinal locations between the two nodes of the NAO.

[18] The dotted areas in Figure 5c identify locations where the Angle index is a statistically significant explanatory variable (with the p -value less than 0.05) in a linear regression model that includes both indices. Given that the smooth NAO index is in the regression model, the Angle index provides substantial additional information about the variability in near-surface zonal wind over much of the North Atlantic sector. Overall, our results imply that the smooth NAO index plays a major role in explaining the 20-yr running mean variability of zonal wind over the North Atlantic sector. The Angle index gives additional information that improves our ability to explain climate variability, especially over the regions corresponding to the shift in the NAO. These regions are marked by the higher R^2 values in the linear regression model which has the Angle index as the only predictor.

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