Relationship between the melting Arctic Sea Ice Extent and North Atlantic Oscillation Index

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Abstract

Arctic Sea Ice Extent (SIE) maintains the ocean circulation at the equilibrium and provides strong feedback in the earth’s climate system. When the Arctic Sea Ice melts in the summer, it results in the oceans absorbing and heating up the Arctic. As Arctic SIE is melting increasing rate, the oceans absorb and heat up further. This contributes into rising sea surface temperature, which has a larger impact on the global atmospheric pressure. Thus, the climate scientists are alarmed that global warming will cause the polar ice caps to melt and that may lead to a critical instability.

In our study, we construct a phase-space using the velocity and acceleration of the Arctic Sea Ice Extent (SIE) as two variables. From data analysis, we show that in recent decades the melting arctic SIE resulted in increasing phase-space volume, i.e., the phase-line distribution function has not been constant along the trajectories. Our aim is to investigate the effect of the melting Arctic SIE on the climate particularly on the North Atlantic Oscillation (NAO) index, a measure of variability in the atmospheric pressure at sea level. Based on a Granger causal model and a conservative Bootstrap statistical test, we find that the changing phase-plane SIE does have a significant (at 0.01 percent) effect on the NAO index. It indicates melting SIE has significant effect on the changing weather pattern of North Atlantic region, specially in Europe and North America. In addition, we see that the yearly median of NAO is greater than the yearly average NAO, which indicates that the distribution of NAO is negatively skewed, even though NAO follows nearly a mean zero stationary process. Our statistical study hints that we will soon see a warmer climate in Eastern USA and Northern Europe. Naturally, a warmer northern Europe would lead to a shrinking SIE, which can be a cause of alarm.

Key Words: Sea Ice Extent , NAO, Granger Causality, Long memory

1 Introduction

In recent decades the Arctic Sea Ice Extent (SIE) is melting at an increasing rate. As a consequence, during summer, SIE is observed less than 30% in current years, compared to decades of 1980’s; see [3]. The melting SIE means the ocean absorbs more heat with respect to previous years and contributes to rising sea surface temperature; which has a larger impact on the global atmospheric circulation [6]. The main source of inter annual variability within the atmospheric circulation pattern is North Atlantic Oscillation (NAO), [7]. NAO is accountable for more than one-third of the variability of the atmospheric pressure at sea-level, [11]. Parkinson and L. Claire (2000) explored the possible link between melting arctic sea ice and NAO index, [12]. However, it does not report any strong evidence in favour of the possible link, [12].

Koslowski (1994) showed that during winters, at the Baltic Sea, the accumulated areal ice volume (AIV) is negatively correlated with the NAO index, [9]. Ronald Kwok (2000) showed for the Arctic Sea, and the Barent Sea; patterns of variability in the ice motion can be linked to the NAO index, [11]. The negative impact of melting SIE at the Labrador Sea on the variability of the NAO index, explained by Kvamsto et al [10]. Bader et al presented a review that examines the impacts of sea-ice loss, and impacts on the NAO, [1]. Caian et al. (2018) presented a link between Arctic sea-ice surface variability and the phases of the
NAO during the winter, see[2]. Kolstad and Screen (2019) used a set of multiple climate models to discover evidence of non-stationarity in the correlation between the sea ice at BarentsKara during autumn, and the winter NAO, [8]. The finding of [8] leads us to question the causality and robustness of the link between the sea-ice extent and NAO index. Hence we study the relationship between melting SIE and the NAO index via Dynamic Granger Causality model, see [4][5].

Except [12], all other studies, i.e.,[9, 11, 10, 1, 2, 8] were done for specific seas of the Arctic ocean and only for the winter season. Such an approach yields a myopic vision of the problem and limits the possibility of a global analysis. One reason for such analysis with myopic vision is all these studies use computationally intensive climate models that limit the possibility of running the analysis over the entire Arctic and North Atlantic regions. On the other hand, statistical analysis is less computationally intensive and easier to implement at the global level, such as Parkinson (2000), see [12]. Our analysis in this paper is along with the spirit of the Parkinson (2000) [12]. Also, the statistical models can outperform more complicated climate forecast models, see [8]. However, a major criticism of the statistical models is: it assumes that the predictor relationships do not change over time, [8]. We address this criticism by adopting the dynamic linear model (aka., dynamic state-space models), see [13]. It updates the relationship between the predictor and the dependent variable dynamically over time.

2 Model and results

We have used two data sources here. The daily SIE data for the Arctic and North Atlantic Oscillation are available from National Snow and Ice Data Center (NSIDC), websites [ftp://ftp.cpc.ncep.noaa.gov/cwlinks/norm.daily.nao.index.b500101.current.ascii] and [ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/north/daily/data/N.seaice.extent.daily.v3.0] NAO data set is available from 1950 and SIE data is available from 1979 to present date. As we wanted to study the yearly effect, we have considered data from 1 January 1979 to September 2019 (40 years data) for both the Arctic Sea Ice Extent and North Atlantic Oscillation. In both sources, from 1 January 1979 to 20 August 1987 the SIE data are available only on alternate days and from 21 August 1987 onward we have daily data. To see the causal relationship between SIE and we have developed some statistical models. We discussed these models one by one in the next section.

2.1 Model for Sea Ice Extent and it’s Phase-Plane Analysis

Here we introduce the model for SIE. Suppose \( x(t) \) is the SIE at time point \( t \). We model it as function of a trend and seasonal component in the following way,

\[
x(t) = \beta_0 + \beta_1 t + \beta_2 t^2 + \sum_{j=1}^{K} \left\{ \sum_{i=1}^{K} \beta_{ji} \sin(i \omega_j t) + \sum_{i=1}^{K} \gamma_{ji} \cos(i \omega_j t) \right\} \epsilon,
\]

where \( \epsilon \) is white noise with \( \mathbb{E}(\epsilon) = 0 \), and \( \text{Var}(\epsilon) = \sigma^2 \), in seasonality component, we consider \( n \) different periodicity with \( \omega_j = \frac{2 \pi}{P_j} \), \( j = 1, 2, \ldots, n \); \( P_j \) is length of the \( j^{th} \) period; \( \beta_{ji} \) is the coefficient corresponding to sine of \( i^{th} \) harmonics of \( j^{th} \) period and \( \gamma_{ji} \) is the coefficient corresponding to the cosine of the \( i^{th} \) harmonics of \( j^{th} \) period. In the model we consider \( K \) harmonics for each period. The first derivative(momentum) and second derivative(acceleration) of the model presented in above Equation are:

\[
x'(t) = \beta_1 + 2 \beta_2 t + \omega \left\{ \sum_{j=1}^{K} \left\{ \sum_{i=1}^{K} \beta_{ji} \cos(i \omega_j t) - \sum_{i=1}^{K} \gamma_{ji} \sin(i \omega_j t) \right\} \right\} \epsilon
\]
\[
x''(t) = \frac{2\beta_2}{\text{trend}} - \omega^2 \left\{ \sum_{j=1}^{n} \left\{ \sum_{i=1}^{K} \beta_{ji} \sin(i\omega_j t) + \sum_{i=1}^{K} \gamma_{ji} \cos(i\omega_j t) \right\} \right\} + \epsilon
\]

Figure 1: (a) The Phase-line plot of SIE vs its Velocity and (b) Velocity vs Acceleration of SIE for 1988 (orange) and 2018 (blue), shows that the phase-line distribution is not constant and that is happening due to melting Arctic SIE.

In Fig. (1), we see that there are major changes in the phase-plane of the SIE. The area of phase-plane for 2018 is more than that of 1988. This major changes in phase-plane of SIE over 30 years may have significant effect on the earth’s atmosphere. Hence, it leads us to investigate the possible causal relationship between the varying dynamics of SIE and NAO index.

3 Causality Between the Melting Arctic SIE and NAO

To Investigate how melting Arctic Sea Ice Extent (SIE) is affecting the different feature of atmosphere, we see the causality between the melting Arctic Sea Ice and NAO. Particularly, we investigate how Arctic SIE is affecting the NAO index? Also we see how variability in NAO is affecting the complex dynamics of SIE. To do this firstly we did the analysis on NAO and see its behavior.

3.1 Long-term Memory of NAO Index (Analysis of NAO index)

We first checked the stationarity and hurst exponent of NAO index. The Table[1] for Hurst Exponent value which is significantly larger than 0.5 and the Fig.[2] time series and autocorrelation plot of NAO index the path of the NAO index has long memory. The P-value for Augmented Dickey Fuller test indicates that the NAO index is mean stationary process. This phenomenon leads us to develop the Null model [4], which tells us that the NAO index is only function of its memory and dynamics of SIE has no effect on NAO index. We propose our alternate model [5] that NAO index is not only the function of its historical memory but also function of the momentum and acceleration of SIE. In equation [5], \(x'(t)\) and \(x''(t)\) are given in the SIE model [2] and [3].
Figure 2: (a) NAO time series over 1979-1982 years of period,(b) Auto correlation function of NAO. We see that NAO index has a long memory

| Methods                        | Hurst Exponent Value |
|--------------------------------|----------------------|
| Simple R/S Hurst estimation    | 0.73                 |
| Corrected R over S Hurst exponent | 0.73               |
| Empirical Hurst exponent       | 0.69                 |
| Corrected empirical Hurst exponent | 0.67              |
| Theoretical Hurst exponent     | 0.53                 |

Table 1: Hurst Exponent of NAO Index indicates that the path of the NAO index has long memory.

3.2 Hypothesis

In this paper, we address the following three questions: Does dynamics of SIE Granger causing on the NAO index? Does the NAO index Granger causing on the momentum of the SIE? Does the NAO index Granger causing on the acceleration of the SIE? Here we present the three hypothesis corresponding to three questions:

1. Does dynamics of SIE Granger causing on the NAO index?

   Null Hypothesis($H_0$):
   
   NAO index is a function of only its historical memory, i.e.,
   
   $$Y(t) = \beta_0 + \beta_1 Y(t - 1) + \cdots + \beta_k Y(t - k) + \epsilon(t)$$
   
   where $Y(t)$ is NAO index at $t$, and $\epsilon(t) \sim N(0, \sigma^2)$

   Alternate Hypothesis($H_a$): NAO index is function of its memory, and historical first derivative(momentum) and second derivative(acceleration) of SIE.

   $$Y(t) = \beta_0 + \beta_1 Y(t - 1) + \cdots + \beta_k Y(t - k) + \gamma_1 x'(t - 1) + \cdots + \gamma_k x'(t - k) + \epsilon(t)$$
   $$+ \alpha_1 x''(t - 1) + \cdots + \alpha_k x''(t - k)$$

   where $x'(t)$ is first derivative(momentum) of SIE and $x''(t)$ is second derivative(acceleration) of SIE estimated from model for SIE.

   Our final objective is to test:
   
   $H_0 : \gamma_1 = \cdots = \gamma_k = 0 = \alpha_1 = \cdots = \alpha_k = 0$ vs. $H_a :$ at least one $\gamma_i \ or \ \alpha_i \neq 0$
Figure 3: (a) Cross-correlation between NAO and first derivative of SIE, (b) Cross-correlation between NAO and second derivative of SIE. Cross-correlation between NAO and derivative of SIE indicates that there exists some weak seasonal correlation between two. The cross-correlation between NAO and the first derivative of SIE ranges between -0.15 to 0.15. Such correlations are considered as weak in nature. However, we cannot completely ignore it. In the second derivative the correlation is very weak, which ranges between -0.01 to 0.01.

The P-value = 0.00206 for ANOVA F-test and more than one $\alpha_i \neq 0$ indicates rejection of Null Model. To see the clear effect we implemented $K = 365$, $K$ is the number of lags of SIE. By implemented the LASSO selection\cite{14} procedure we dropped the lags which have no significant effect over NAO. It means dynamics of SIE has statistically significant effect on NAO.

2. Does NAO Index Granger Causing on the First Derivative of the SIE?

*Null Hypothesis* ($H_0$):

Suppose $Y(t)$ is the first derivative (momentum) of SIE at time $t$, which is function of its historical first derivative only, i.e.,

\[
Y(t) = \beta_0 + \beta_1 Y(t - 1) + \cdots + \beta_k Y(t - k) + \epsilon(t)
\]

where $Y(t)$ is first derivative of SIE at $t$, and $\epsilon(t) \sim N(0, \sigma^2)$

*Alternate Hypothesis* ($H_a$): First derivative of SIE is function of its historical first derivatives, and NAO index.

\[
Y(t) = \beta_0 + \beta_1 Y(t - 1) + \cdots + \beta_k Y(t - k) + \alpha_1 x(t - 1) + \cdots + \alpha_k x(t - k) + \epsilon(t)
\]

where $Y(t)$ is momentum or first derivative of SIE, and $x(t)$ is the NAO index.

Our final objective is to test:

$H_0 : \alpha_1 = \cdots = \alpha_k = 0$ vs. $H_a :$ at least one $\alpha_i \neq 0$

The P-value = 0.00356 for ANOVA F-test indicates rejection of Null Model. (We considered the raw values of SIE). It means dynamics of SIE has statistically significant effect on NAO.

3. Does NAO Index Granger Causing on the Second Derivative of the SIE?

*Null Hypothesis* ($H_0$):

Suppose $Y(t)$ is the second derivative of SIE at time $t$, which is function of its historical second derivatives only, i.e.,

\[
Y(t) = \beta_0 + \beta_1 Y(t - 1) + \cdots + \beta_k Y(t - k) + \epsilon(t)
\]

where $Y(t)$ is second derivative of SIE at $t$, and $\epsilon(t) \sim N(0, \sigma^2)$

*Alternate Hypothesis* ($H_a$): Second derivative of SIE is function of its historical derivatives and NAO index.
\[ Y(t) = \beta_0 + \beta_1 Y(t-1) + \cdots + \beta_k Y(t-k) \\
+ \alpha_1 x(t-1) + \cdots + \alpha_k x(t-k) + \epsilon(t) \]  \hspace{1cm} (9)

where \( Y(t) \) is second derivative of SIE, and \( x(t) \) is the NAO index. Our final Objective is to test:

\[ H_0 : \alpha_1 = \cdots = \alpha_k = 0 \text{ vs. } H_a : \text{at least one } \alpha_i \neq 0. \]

If test rejects null hypothesis (\( H_0 \)) then that means at-least one lag-value of NAO index statistically influence the acceleration of SIE. The P-value = 0.005901 for ANOVA F-test indicates rejection of Null Model. It mean NAO index has statistically significant influence the acceleration of SIE.

4 Results Consolidation

The phase-plane analysis of SIE indicates growing phase-plane area over the year due to melting Arctic sea ice. Hurst exponent for NAO > 0.5 and ACF plot implies NAO has long memory. Dickey Fuller Test indicates that NAO is mean stationary process. CCF function indicates that there is lead and lag cross correlation between NAO and derivatives of SIE. The Lasso selected Granger Causal model shows that the derivatives of SIE has statistically significant effect on NAO and vice-versa.

The very small P-value for ANOVA F-test indicates rejection of all the Null Models discussed above. Analysis indicate marginal distribution of NAO is though stationary; but it is negatively skewed. We observed median NAO index is greater than mean NAO index. This means that more than 50% time NAO tends to be in positive horizon, however when it goes to negative horizon, it observes very large negative values. Therefore our analysis indicates that as most of the time NAO experience positive values it experiences warmer weather in northern US and Europe. However, negatively skewed NAO indicates that NAO experience large drops which yield colder weather in Europe and US.

5 Summary

The derivative of SIE has significant effect on NAO index; as well as the NAO index has significant effect on derivatives of SIE at 0.01% level of significance. However, the strength of the Granger type lead-lag correlation is weak in nature. The strength of the correlation is significant enough so that we cannot ignore it. However, not enough to improve the predictive power of the model.

Based on the Granger causal model, the conservative Bootstrap statistical test indicates that the changing phase-plane SIE has a significant effect on the NAO index at 0.01% level of significance. In addition, we see that the yearly median of NAO is greater than the yearly average NAO. It indicates that the distribution of NAO is through a mean zero stationary process, but it is negatively skewed. It means we see a statistically more warm climate in Eastern USA and Northern Europe. Also statistically more cold and drought-prone climate in Southern Europe.

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Figure 4: Relationship between predicted and actual value of NAO
Figure 5: Plot of SIE: Velocity of SIE vs Acceleration of SIE

Figure 6: Left: NAO time series plot for mean (black) and median (red). We take yearly average values for both mean and median. We see that median is greater than mean here. More values of NAO are in positive range. Right: histogram plot of the difference values of mean and median. Clearly we see that it is negatively skewed. We see that SIE increases when NAO has tendency to shift towards positive.
Figure 7: Left: NAO time series plot for mean (black) and median (red). We take monthly average values for both mean and median. We see that median is greater than mean here. More values of NAO are in positive range. Right: histogram plot of the difference values of mean and median. Clearly we that it is negatively skewed. We see that SIE increases when NAO has tendency to shift towards positive.

Figure 8: Using dynamic linear model we see the trend of the coefficients of Sea Ice Extent.