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Modelling the Evolution of Arctic Sea Ice Extent

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Abstract

Over the last forty years, the Arctic sea ice extent has decreased at an average rate of 12.8 percent per decade in summer. This is obviously due to climate change through an increase of greenhouse gas emissions. In this project, we will try to analyze the variation of sea ice extent in terms of some climate patterns using statistical learning techniques.

1. Introduction

1.1 Importance of Arctic Ice Caps

Over the last fifty years, the Arctic ice has been melting at a much more drastic rate than in the past centuries. Although the melting has a few positive aspects, namely the creation of marine shipping routes in the region, the decrease in area of the Arctic ice cap comes with many troublesome consequences such as a decrease in the Arctic's surface albedo, disturbances of ocean circulations and extreme weather.

The Arctic melting has a direct impact on global warming because it causes the earth to absorb more heat. The decrease in ice cover of the Arctic territories reduces the albedo of the Arctic surface, the albedo being a measure of how well a surface reflects sunlight. Since ice covered with snow reflects about 85% of sunlight while open water reflects only 7%, it is observed that the Arctic surface albedo decreases (Langleben, 1969). In fact, an increase in the area of ice-free surfaces in the Arctic will lead to less sunlight being reflected, causing our planet to absorb more heat. As a result, the temperature of our atmosphere increases. Moreover, the Atlantic Ocean Meridional Overturning Circulation (AMOC), which plays a primordial role in the global thermohaline circulation that distributes great amounts of heat and freshwater, has undergone many changes during the past glacial-interglacial cycles, and these changes are strongly correlated with the glacial ice discharges from the Arctic region into the North Atlantic (Swingedouw et al., 2009). The Greenland ice sheet has diminished due to global warming, causing the process of convection to be also reduced. Since the convection process is essential to the production of dense water which contributes to the AMOC, this melting has caused the AMOC to slow down. Because the AMOC is responsible for carrying warm surface water northward from the tropics to Western Europe, its decrease in movement will consequently cool down Western Europe. Furthermore, the Arctic ice cap acts as an insulator between the Arctic Ocean and the atmosphere. Indeed, in winter, the ocean's temperature is warmer in comparison to the air in the northern region, and the ice layer prevents the heat from the ocean from warming up the atmosphere. However, when the ice becomes too thin, heat can escape easily to the atmosphere. More specifically, the heat escapes from leads and polynyas, which are small openings in the ice cover. Also, about half of the heat exchanges in the Arctic happen through these small ice openings. Therefore, with more leads, polynyas and thinner ice, the Arctic atmosphere will warm, and this will influence the global atmosphere circulation.

1.2 Effect of Global Climate

Sea ice regulates the global climate for three main reasons: the albedo effect, the water mass stratification and the insulation effect. Indeed, sea ice acts as a reflective surface which sends back a portion of solar rays back into space as well as an insulator between the cold Arctic atmosphere and the warmer ocean during winter months. Melting of sea ice also inputs lower density freshwater into the ocean.

With the melting of sea ice in polar areas, the earth absorbs more energy from sunlight, and consequently, the temperature elevates. This change contributes to more sea ice melting, which exemplifies a positive feedback loop (Zheng et al., 2019). Melt ponds speed up the melting of sea ice during summer since they decrease albedo and contribute to darkening the Arctic. In fact, water albedo is significantly lower than ice's (Lei, et al., 2016). Moreover, global warming caused by CO_2 was found to increase much more if ice sheets were not considered in the model used (Pollard & Thompson, 1994). Hence, the steady diminution of sea ice area could hasten warming.

Sea ice also affects salinity which is a factor that regulates the global ocean conveyor belt. In fact, water beneath sea ice surfaces has higher salt concentration and is therefore denser. The melting of sea ice could cause disruption in the thermohaline circulation since melted ice is a significant source of freshwater, which possesses lower density. Water near the poles needs to sink under the surface in order to be taken to warmer areas near the Equator. However, with freshwater being incorporated in polar areas, this phenomenon cannot happen. "Very pronounced water mass stratification" was observed to be caused by "freshwater [...] outflow" (de Vernal & Hillaire-Marcel, 2000).

The ocean and the atmosphere are correlated in the regulation of the earth's climate. Sea ice acts as an insulator in winter months between the cold Arctic atmosphere and the warmer ocean water. By isolating the atmosphere, sea ice "reduces evaporation from the ocean, resulting in a decrease in water vapour and cloud cover" (Zheng et al, 2019). However, decreased cloud vapour cannot be taken as a direct indication of heating diminution since clouds can cool or heat depending on their specific characteristics.

1.3 Factors Causing the Melting of the Arctic

A suspected cause of the Arctic ice melting is the positive feedback loop, a process in which ice loss leads to even more ice loss. In fact, as ice declines, the areas of open water absorb more heat due to albedo. As a result, this increased amount of heat will melt even more ice in the Arctic territories. However, according to recent studies, this feedback is not the main cause of the melting. The only plausible cause of such consistent decrease in surface area of the Arctic ice is the increase of CO_2 in the atmosphere. Indeed, a linear relationship was observed between the monthly-mean September sea-ice area and cumulative carbon dioxide emissions. The linear relationship shows a sustained loss of 3 ± 0.3 square meters of September sea-ice area per metric ton of CO_2 emission (Notz & Marotzke, 2012). Hence, the decrease is caused by the increase of greenhouse gases emissions which accelerate climate change.

2. Data and Methodology

For our project, we wanted to understand the variation of the Arctic sea-ice extent (SIE) over time and the dependence between this variation and the global surface temperature anomalies (GTO)[1]. The data for the Arctic sea-ice extent are available at the National Snow and Ice Data Center or at the Arctic Ice Graphs website. Instrumental data are available from 1979 to today and reconstructed data are available from 1850 to today. The data of the Global surface temperature anomalies are available at the National Oceanic and Atmospheric Administration and are from 1880 to today. Figure 1 shows the variation of the GTO over time. One can see clearly that, over

[1] In climate change studies, temperature anomalies are more important than absolute temperature. A temperature anomaly is the difference from an average, or baseline, temperature. The baseline temperature is typically computed by averaging 30 or more years of temperature data (This definition is given by the National Oceanic and Atmospheric Administration).

the last 40 years, the GTO have only positive values, and that these values increase over time. Figures 2 and 3 respectively show the daily and the monthly variations of the SIE variable. The daily data are plotted only for the period of 1978 to 2019 to ensure a high-quality figure. From Figure 2, one can see that the daily SIE data has a significant cyclic component and is autocorrelated over time. From Figure 3, one can see the monthly behavior of the SIE data. September is the month with the smallest sea ice extent, while March is the month with the largest sea ice extent. Also, the loss of the ice extent in September is larger than that in the other months. Figure 5 shows the satellite images of the SIE in September 1979 and September 2019.

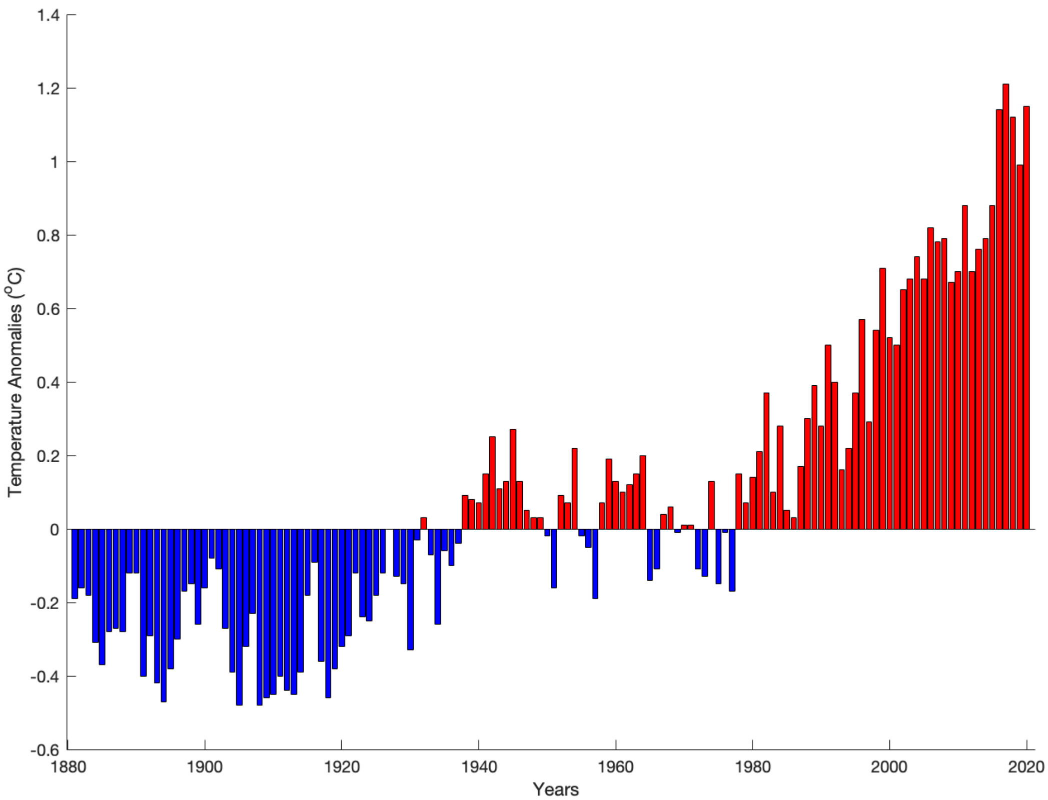

FIGURE 1: GLOBAL SURFACE LAND AND OCEAN TEMPERATURE ANOMALIES FROM 1880 TO 2019 (DEGREES CELSIUS). A POSITIVE ANOMALY INDICATES THAT THE INSTRUMENTAL TEMPERATURE WAS WARMER THAN THE CALCULATED AVERAGE, WHILE A NEGATIVE ANOMALY INDICATES THAT THE INSTRUMENTAL TEMPERATURE WAS COOLER THAN THE AVERAGE.

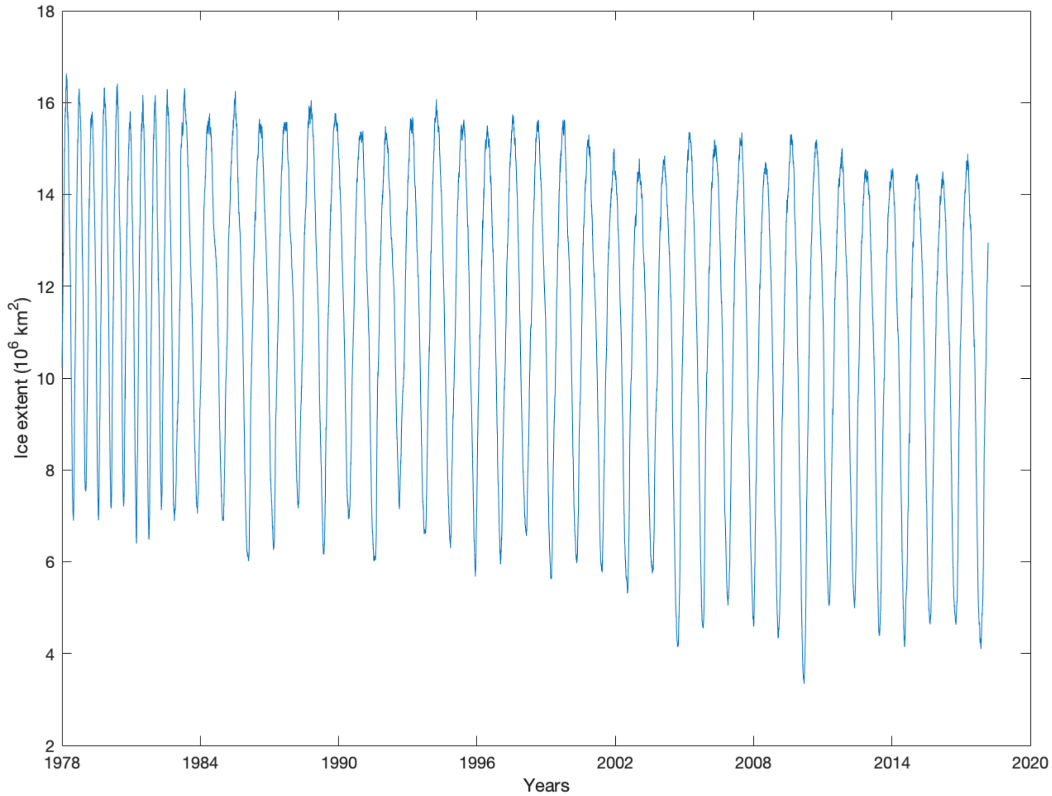

FIGURE 2 : DAILY DATA
FOR THE ARCTIC SEA ICE EXTENT FROM 1978 TO 2019.

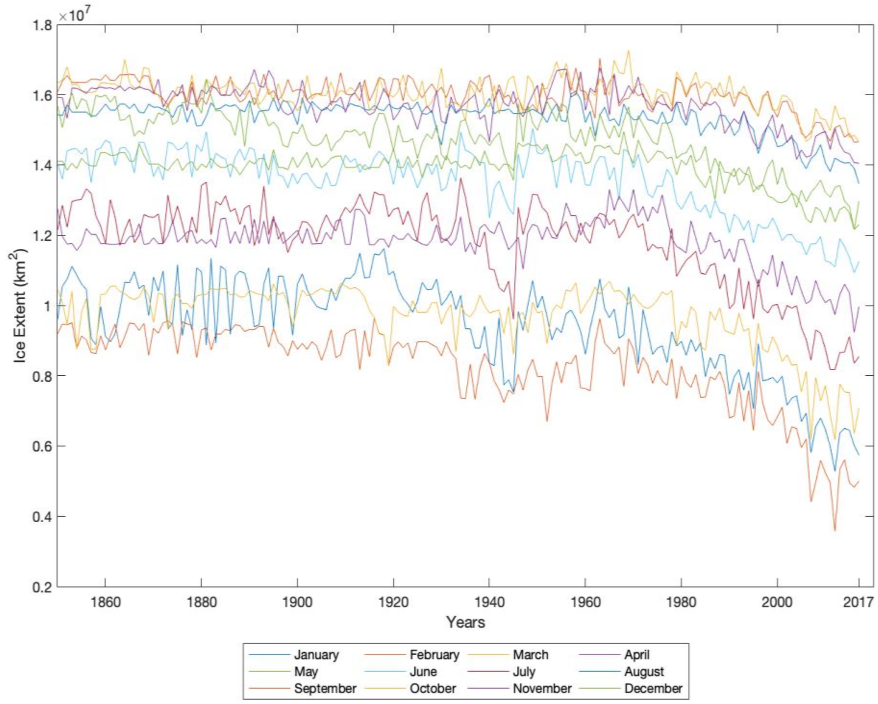

FIGURE 3: MONTHLY DATA FOR THE ARCTIC SEA ICE EXTENT FROM 1850 TO 2019

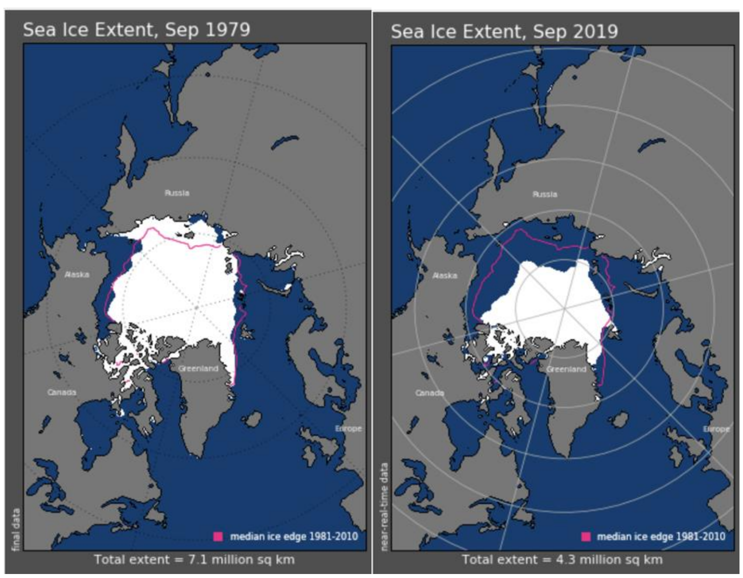

FIGURE 4: ARCTIC SEA ICE EXTENT IN SEPTEMBER 1979 AND SEPTEMBER 2019 (SOURCE: NATIONAL SNOW AND ICE DATA CENTER).

For our project, two models are used to understand and describe the temporal variations in the SIE data. The first model is called the ARIMA (Autoregressive integrated moving average) model. This model aims to describe and forecast the monthly SIE data. The second model is the linear regression model which will be used to understand the monthly dependence of the SIE data and the GTO data. ARIMA analysis can be separated into three parts: identification, estimation and forecast. In the identification section, different types of correlation including autocorrelation are computed in order to find the best fitting model. Subsequently, estimation of parameters is used to fit the model to the series. Goodness of fit statistics are useful to compare different models. When data has been treated, forecast can be done, and estimated confidence intervals can be established. ARIMA models have three main characteristics: Autoregressive (P), Integrated (D), and Moving-Average (Q). For autoregressive models, the linear combination of past values is used to compute the regression and provide a forecast. Autoregressive models require the data to be stationary. In fact, fairly little can be extrapolated from non-stationary series analysis. Since stationary series have constant mean and variance, any trend and seasonality have to be removed first by differencing. ARIMA takes this requirement into account by "computing the differences between consecutive observations." (https://otexts.com/fpp2/stationarity.html) For a linear trend, the D factor, which is the order of differencing, would be one. More complex trends would require further differencing and logarithms for example. The differenced series would therefore be $y'_t=y_t-y_{t-1}$.Similarly, to remove seasonality, the difference between the data of a month and the data of the same month from the previous year would have to be computed. Hence, ARIMA models integrate the seasonality factor into their calculations. Past forecasting errors are also computed into weighted moving-averages, which are then plotted into a regression. To perform the ARIMA analysis, one can use the Forecast package available in CRAN (Hyndman, et al., 2020).

3. Results

3.1 The ARIMA Analysis

First, the ARIMA model based on all the monthly SIE data over the past 40 years was produced. With this approach, the seasonality of the data can clearly be seen in the zigzagging pattern of the graph and is taken into account by the ARIMA model for the forecast. Despite this seasonality, a clear downward trend is visible, indicating that, although the ice melts and refreezes every year, every time it refreezes, its area is smaller than it was the year before. Figure 5 shows the decomposition of SIE data into trend, seasonal and random components and Figure 6 shows 10 years of monthly forecasts including the 95% confidence interval using the ARIMA model. From Figure 5, one can see clearly the significant decreasing trend and seasonality effect. From Figure 6, one can see that the decreasing will continue in the future.

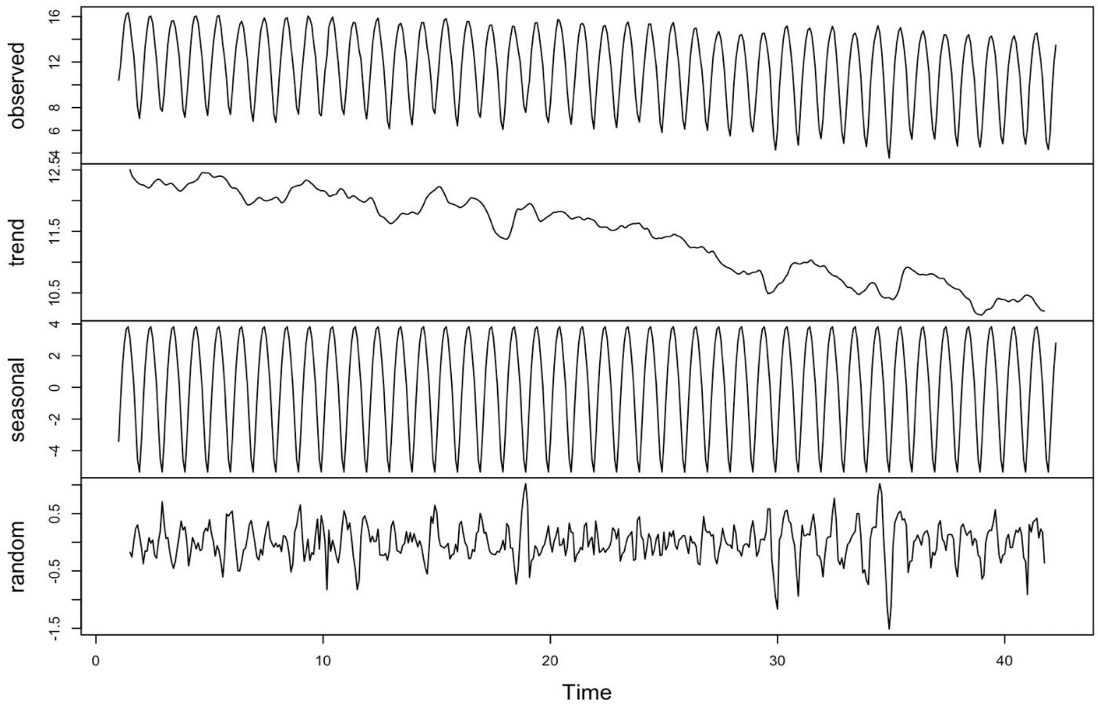

FIGURE 5: DECOMPOSITION OF THE MONTHLY SIE SIGNAL OVER THE 40 LAST YEARS

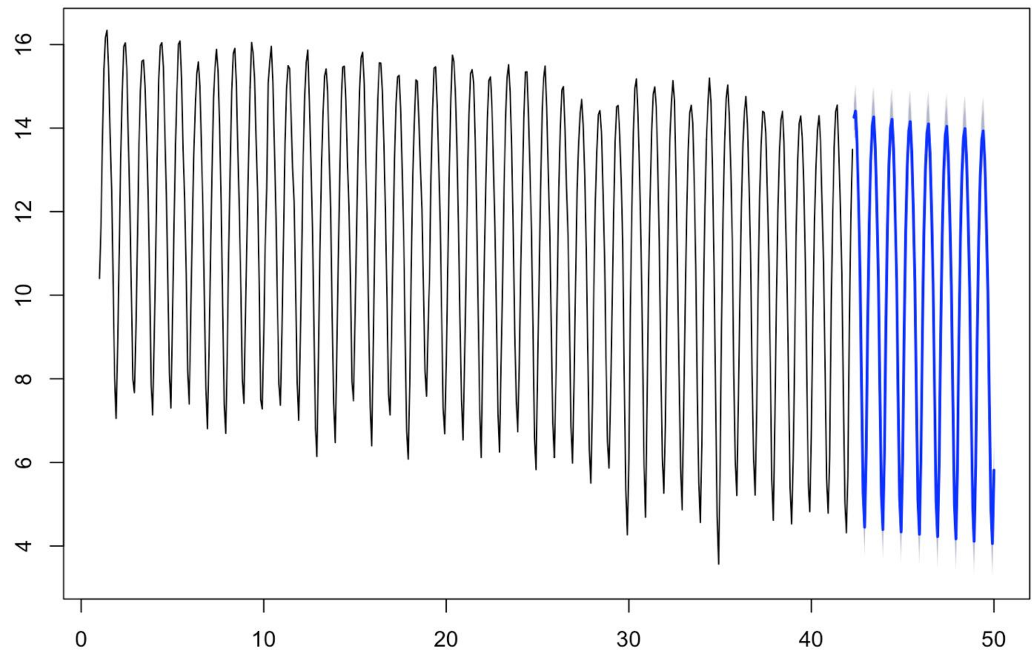

FIGURE 6: THE ARIMA 10 YEARS MONTHLY FORECAST FOR SIE (10^6 KM^2) WITH THE 95% CONFIDENCE INTERVAL

3.2 The Regression Analysis

Linear regression was then used to model the SIE according to the GTO for each month separately and predict how the monthly SIE data would change if the temperature anomaly were to rise by 1 to 2 degrees. The results and the 95% confidence intervals are displayed in Figure 7. One can see from this figure that the Arctic ice extent will decrease significantly if the temperature anomaly goes up by one degree, particularly in July, August, and September, where the slope is particularly steep.

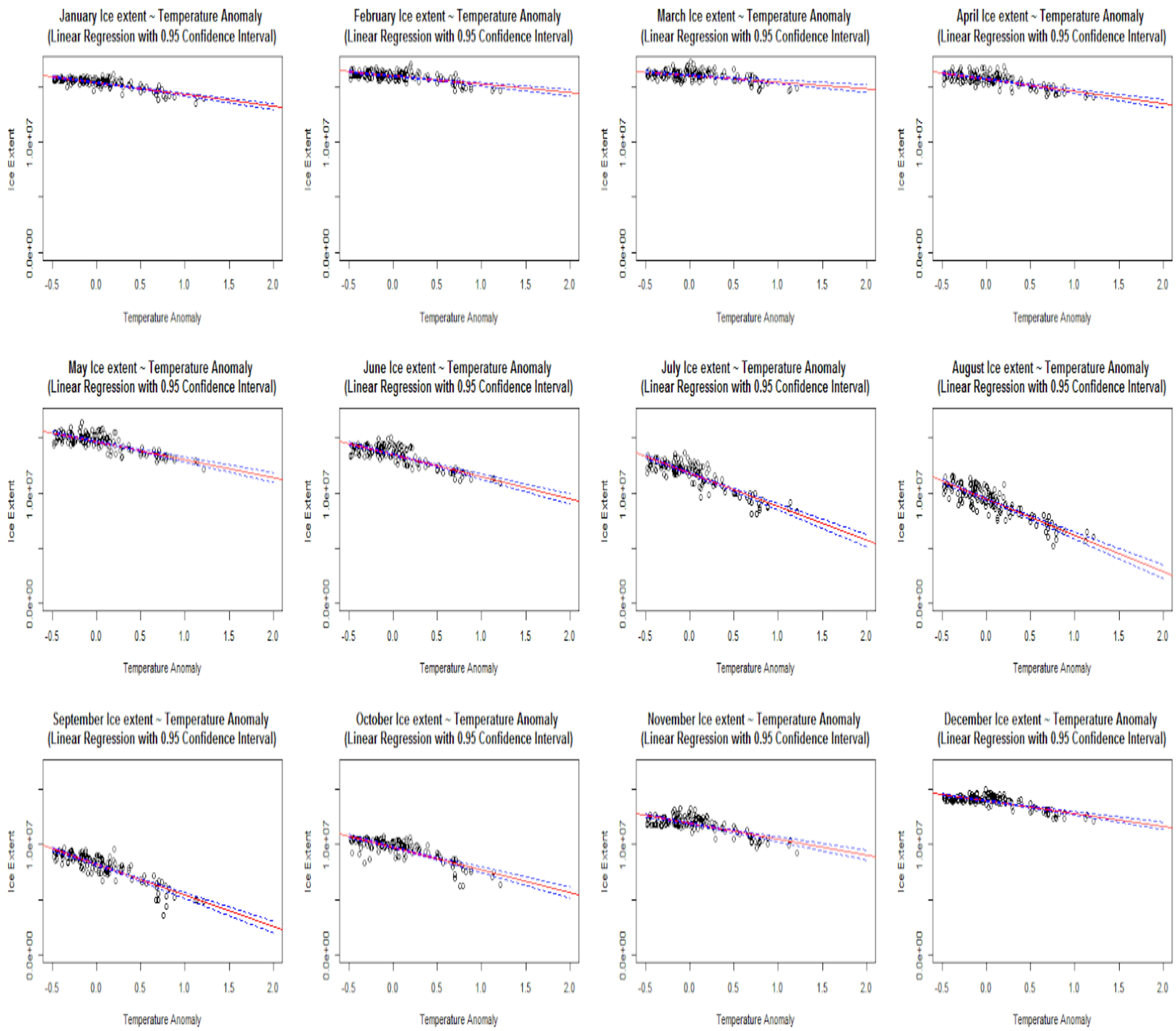

FIGURE 7: LINEAR REGRESSION MODEL FOR THE MONTHLY SIE DATA USING GTO AS COVARIATE

4. Discussion

4.1 Consequences of the Melting

The melting of the Arctic ice is a plausible cause for the frequent extreme weather phenomenon across the Northern Hemisphere mid-latitudes. The temperature gradient between the Arctic and lower altitudes allows the driving of the jet stream wind. However, if the Arctic warms up, this difference will be lower, and as an effect, cause the slowing of upper-level zonal winds. This weakening of winds would lead to a more meandering and slow Eastward progression of ridges and troughs which promote amplified jet-stream trajectories. Amplified jet-stream trajectories favor the likelihood of extreme weather (Francis & Vavrus, 2012). On one hand, deep troughs would result in events such as the endless string of snowstorms in the U.S east coast and in Western Europe. Ridges, on the other hand, bring unusually warm conditions such as severe droughts and heat waves over the Northern Hemisphere (Francis & Skific, 2015).

4.2 Possible Future Solutions

There exists a number of technologies that have been developed to restore Arctic ice. For instance, the non-profit Ice911 has created microscopic reflective sand, consisting of hollow microspheres that float on water which could act as ice. The microspheres used are made of silica, silicon dioxide. When the substance is sprayed on the ocean's surface, it becomes a white slush which has the same reflective properties as ice. Thus, it would have the same albedo as ice, reflecting the same number of light rays instead of absorbing it like water (Fiekowsky, 2019).

Another technique is ice thickening, which has been used by oil companies for many decades to build ice roads for oil production. The technique consists in taking action during the winter months when the Arctic is in complete darkness and temperatures can go down until -50 degrees Celsius. Sea water from the depths of the ocean is sprayed onto the pre-existing ice surface, and it freezes within minutes creating a thicker ice layer. This technique could be a great solution since one meter of extra ice can last throughout the summer. Restoring that protective reflective sheet of ice will slow the warming of the oceans (Fiekowsky, 2019).

In fact, researchers from the Arizona State University have proposed to use wind-powered pumps to restore the ice extent in certain Arctic regions, called the Arctic Ice Management. Their research shows that adding one meter of ice could allow us to recreate the ice cap of nearly 17 years prior to today. Plus, the extra layer of ice could counter an increase in the atmosphere's temperature of one-degree Celsius. Unfortunately, such a project could cost 50 billion dollars annually, which is why the technique hasn't been used yet.

5. Acknowledgments

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