The Severe Storm Index: Gauging our progress in the "War-Effort" against climate change

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Abstract

While it is difficult, if not impossible, for most humans to conceptualize CO_2 levels or ocean temperatures, we are very aware of the growing number of storms and their increase in severity. Indeed, according to the National Weather Service, the number of severe storms has increased in the United States from 1 – 3/decade in the 1950s through the 1980s, to 8/decade in the 1990s, 30/decade in the 2000s, and 54/decade in the 2010s. Here we argue that a Severe Storm Index (SSI), calculated by dividing the sum of storms/decade by 10, is readily intelligible and can be used as a gauge to inform our behavior as we seek to correct climate change in the United States via a large-scale, fully integrated, "war-time like" effort.

Introduction

Humans must be able to track climate change to address climate change

Most acknowledge climate change, noting more hot days, stronger storms, more floods, more droughts, and more forest fires. The impact is seen and felt around the world. Recent reports indicate that climate change also is a source of high anxiety, especially for our children (1-3). It is, then, imperative that we address this threat to the best of our ability. Like any other problem, the population must be able to gauge climate change, if they are to address climate change. Once we can gauge climate change, the people will need a "war-time like" effort, not unlike that initiated during World War II (WWII), to systematically address the problem at the national, state, local, and individual level. Along with the recent passage of the Inflation Reduction Act, an effective solution to the growing threat of climate change will require the highly organized use of all of our resources, human and otherwise. We must unify to address this impending threat, from the top down and from the bottom up.

Results

So how can human beings best gauge climate change?

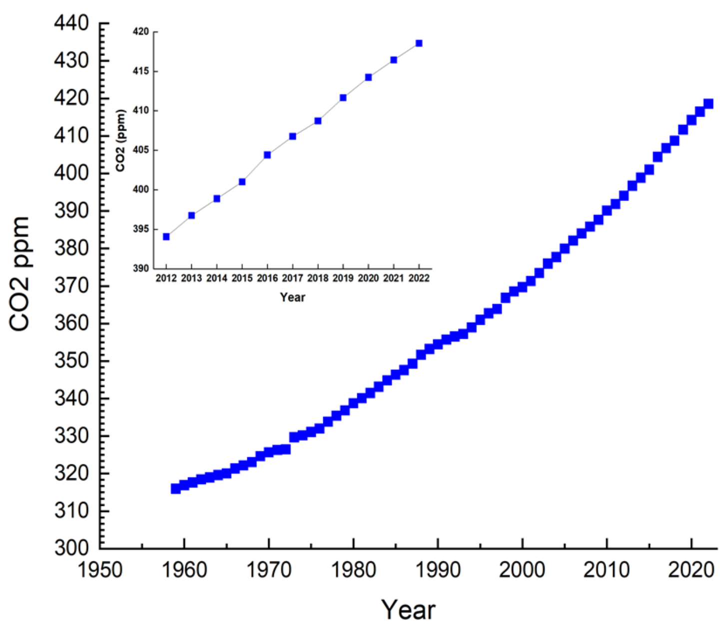

Fig 1. Worldwide carbon dioxide (CO_2) levels in the atmosphere in parts per million (ppm) as a function of year (1959 to 2022).

Global atmospheric CO_2

Global atmospheric carbon dioxide (CO_2) levels are rising, and evidence shows that human activity is responsible for the rise (4). Fig 1 shows the steady increase in worldwide CO_2 levels in atmosphere from 1959 to 2022. The insert hones in on years 2012 to 2022, again showing a continuous and unrelenting rise in atmospheric CO_2 (5). While climate scientists warn that we must limit this increase, rising CO_2 levels are impossible for humans to detect and, thus, difficult for us to conceptualize.

Atlantic ocean heat content

Along with rising atmospheric CO_2 levels, ocean temperatures also are rising. Thus, as shown in Fig 2, Atlantic Ocean Heat Content, as assessed via the vertical mean temperature from 0 to 700 meters below surface, also has risen steadily, accelerating sharply after 1990 (6). Indeed,

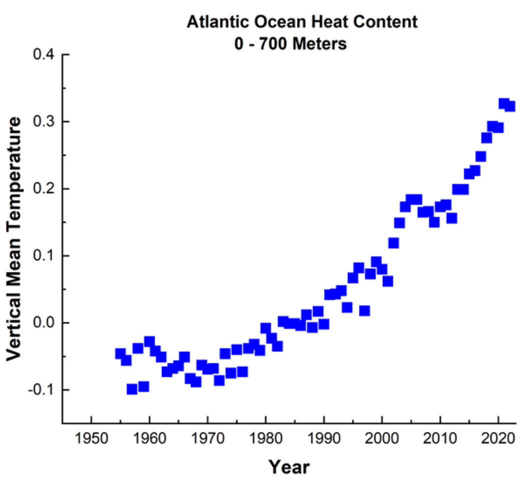

Fig 2. Global Ocean Heat Content as a function of year (1955 to 2022).

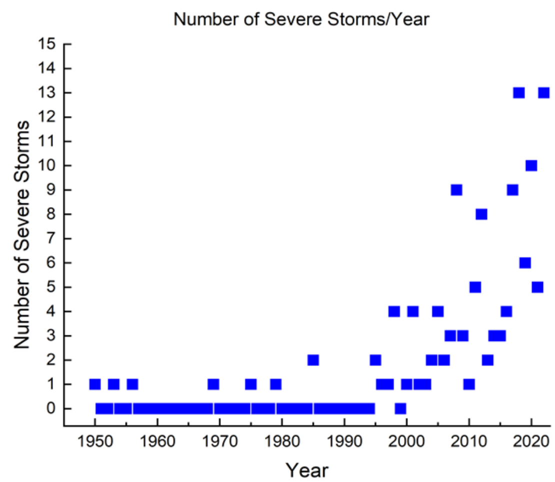

Fig 3. Number of Significant Weather Events (Severe Storms) listed annually from 1950 through 2022.

the two appear to go hand-in-hand, as the increase in Atlantic Ocean Heat Content is highly correlated with the increase in atmospheric CO_2, $r=0.97$, $p < 0.0001$. Like atmospheric CO_2, however, ocean temperature also does not serve as a ready gauge for individual tracking of climate change, or of our effective, or ineffective, effort to address the rapidly growing problem.

Severe storms

Rising ocean temperatures contribute to a greater number of severe storms and to storms that carry more water leading to more damage and to more loss of human life (7). In accordance, like Atlantic Ocean Heat Content, the number of severe storms in the United States as tracked by the National Weather Service (NWS) (8) also has risen sharply, particularly since the mid-1990s (see Fig 3). The NWS has sought to document every significant severe weather event, tropical landfall, winter weather event, and flooding event across the nation since the 1950s. Importantly, analysis with Pearson's and Spearman's nonparametric correlation coefficients show strong positive relationships whereby the increase in Atlantic Ocean Heat Content over time is significantly correlated with the increase in the number of severe storms, $r = 0.78$, $p < 0.0001$; $r=0.81$, $p<0.0001$, respectively. Indeed, a regression model accounting for the numerous years with zero severe storms, a zero-inflated negative binomial regression model, confirms this highly significant relationship where a 1.0 degree increase in average Atlantic Ocean temperatures corresponds to a multiplicative increase in the log count of severe storms (est. coefficient: 7.8, SE = 1.53, z= 5.11, $p<0.0001$). Additionally, the zero-inflated portion of our model shows that as the ocean gets warmer, years without any severe storms become increasingly rare as the log-odds of having zero storms with a 1.0 degree rise in Atlantic Ocean temperatures are nearly zero (est. coefficient: -24.11, SE= 8.47, z= -2.85, $p<0.0044$). When summed across each decade (see Fig 4, left panel), the total number of severe storms recorded in the United States by the National Weather Service has increased from 3 such storms in the decade of the 1950s, 1 in the decade of the 1960s, 2 in the 1970s, 2 in the 1980s, 8 in the 1990s, 30 in the 2000s, and 54 occurring in the decade spanning from 2010 – 2019. Post hoc Tukey's Tests of a significant one-way analysis of variance (ANOVA), $F(6, 54) = 15.53$, $p < 0.0001$, confirmed a significant increase in the total number of severe storms in the 2000s and again in the 2010s compared to all decades prior, ps < 0.05.

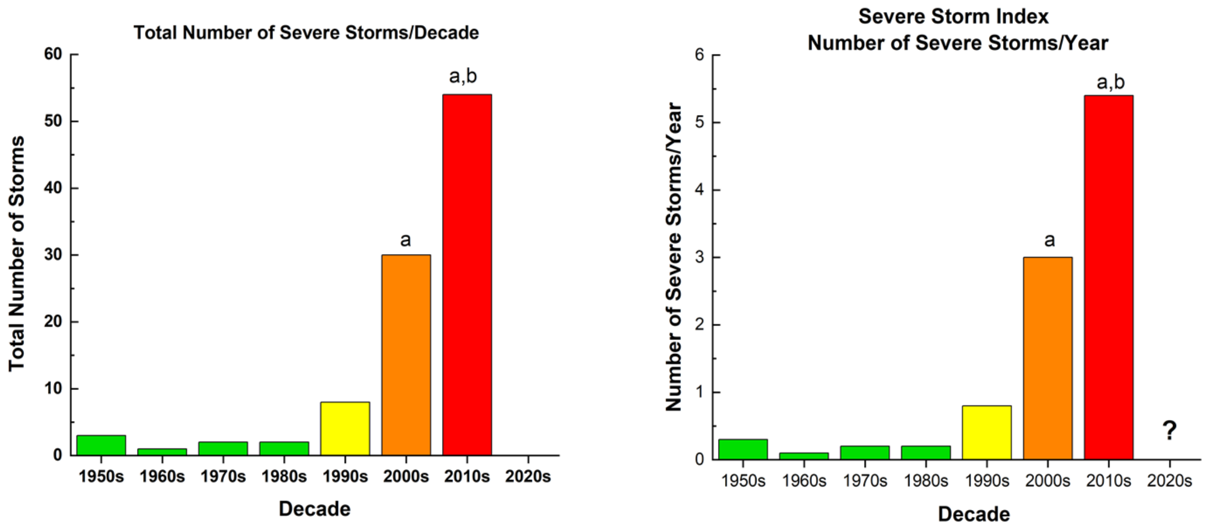

Fig 4, left panel. Total number of Significant Weather Events (Severe Storms) for each decade. Weather.gov/mob/events. a > 1950s-1990s; a,b > 1950s – 2000s, $p < 0.05$. **Fig 4, right panel.** Number of Significant Weather Events (Severe Storms)/year for each decade. Weather.gov/mob/events. a > 1950s-1990s; a,b > 1950s – 2000s, $p < 0.05$.

Severe Storm Index

If we are going to gauge our progress in addressing climate change, which is essential to effectively modify our behavior, we will do best to assess our progress, not by decade, but by year (see Fig 4, right panel). When considering the number of severe storms/year averaged across each decade in the United States, this number increased from 0.3/year in the 1950s, 0.1/year in the 1960s, 0.2/year in the 1970s and 1980s, 0.8/year in the 1990s, 3/year in the 2000s, and 5.4/year in the 2010s. The National Weather Service reported 10 severe storms during the year of 2020, 5 in 2021, and 13 in 2022, contributing to a current running average of 8.3 severe storms/year in the present decade.

This number, the average number of severe storms occurring each year as calculated using the data reported by the NWS, is referred to here as the **Severe Storm Index (SSI)**. While the number will vary from one year to the next, the number of severe storms occurring each year is something we are highly cognizant of, and something we can count in order to gauge our progress in addressing the climate crisis in an effective and timely fashion. A composite figure (see Fig 5) shows all severe storms as reported by the NWS, with the size of the circle increasing with the corresponding increasing level of CO_2, and the color of the circle changing from blue to red indicating a corresponding increase in the ocean temperature. As is evident from this figure, since 2008, nearly half of the years in the past 15 (i.e., seven years) have experienced severe storm counts greater than 5.4/year, i.e., greater than the average of the last decade. Our goal must be to flatten this curve (something the public now understands because of the COVID-19 pandemic), preferably by reducing from a current running average of more than 8.3 severe storms/year to 3 severe storms/year and, ultimately, to 1 severe storm/decade in the United States – i.e., a return to levels seen in the 1950s, 1960s, 1970s, and 1980s.

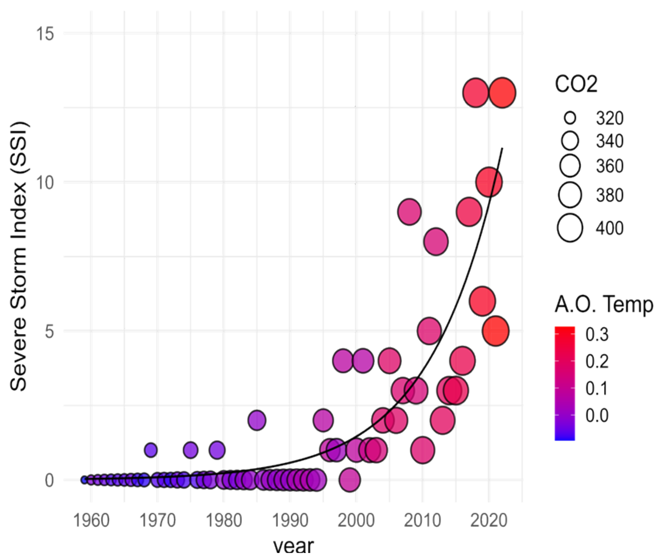

Fig 5. Annual number of Significant Weather Events (Severe Storms, 1959 to present) as a function of CO_2 levels and Atlantic Ocean Temperatures. The size of each point represents CO_2 levels, and the color indicates Atlantic Ocean Temperature at a depth of 700 meters. A trend line indicates the average observed increase of severe storms based on the best fit centered negative binomial (GLM) regression model, which accounts for clustering, variance inflation, and overdispersion.

A "war-time like" effort

This will require a concerted and organized effort, a national "war-time like" effort akin to that implemented during WWII. Indeed, in examining Figure 5 each of us can anticipate where these numbers are going. Our final analysis employs two distinct modeling approaches to project the future increase in severe storm counts from 2023 to 2040 (see Fig 6). The left panel shows a trend based on the Generalized Additive Model (GAM), a conservative linear projection that predicts a steady rise in storm counts/year. The right panel shows a trend based on the best fit of the current data which is a generalized linear mixed model using the available data, CO_2 and Atlantic Ocean temperatures, as centered predictors in the model. Using a negative binomial distribution accounts for data complexities stemming from non-independence and overdispersion inherent to the variation in historical severe storm counts which cannot be adequately explained by a simpler Poisson model. Thus, the data shown in the right panel of Fig 6 extends this best fit trend to represent a robust assessment of the expected increase in severe storm counts while considering the complex nature of the data. This model, guided by the available data, projects an average of 25 severe storms/year by 2030 and 60 severe storms/year by 2040. Thus, in less than 20 years-time, with an average of 5.4 severe storms/year in the last decade, the United States may experience a near 12-fold increase in the number of severe storms annually. These are sobering numbers. Further, these severe storms also are growing more deadly and more costly (9). The National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information reported that the year 2020 saw a record 22, 2021 an additional 20, and 2022 an additional 18 separate billion-dollar weather and climate disasters in the United States (these figures also include draughts, heat waves and forest fires – events not included in the Severe Storm Index) (10-12). The cost of these storms in 2022 is estimated at $165.0 billion

(12)). These trends are not sustainable, they are not affordable, and they are not acceptable in the loss of resources and certainly not in the loss of life, human and otherwise.

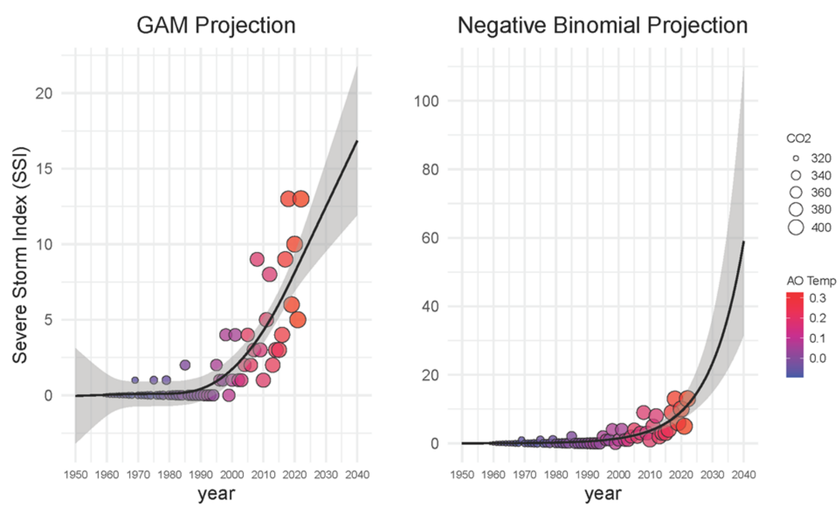

Fig 6. Projected Severe Storm Counts (2023-2050): Conservative linear trend (GAM) on the left and multiplicative-like trend based on the best fit of available data (Negative **Binomial**) on the right. The general additive model suggests a steady rise in storm counts, while the centered negative binomial (GLM), characterized by a steep rise, captures the overdispersion within the data. These modeling approaches encapsulate both linear and multiplicative scenarios, accounting for the data's complexity. Gray Shading represents 95% confidence interval.

Discussion

Quite fortunately, the United States Congress agrees and has now passed the Inflation Reduction Act which seeks to reduce our nation's greenhouse gas emissions by 40% by the year 2030 (13). This is remarkable. But, this goal cannot be accomplished from either the top down, or from the bottom up, alone. Effectively addressing the climate crisis, averting climate disaster involving more than 100 severe storms projected in the present decade alone, will require a "war-time like" effort, not unlike that initiated during WWII, organized by the Federal Government, in coordination with the State Governments, in coordination with local municipalities, and involving the contribution, the work, of every able American. Indeed, if we are going to make the most of the Inflation Reduction Act, perhaps even exceed expectations, which is imperative, we will need to be organized, we will need to be unified, we will need to work cooperatively together, and we will need to use the Severe Storm Index to gauge, and thereby to ensure, our success.

One vehicle for orchestration of this critical unified effort is the development of a data dashboard, not unlike that successfully created and employed by Johns Hopkins University for the tracking of COVID-19 outcomes across the nation. Along with national data, state input regarding the needs and opportunities related to climate could be provided via such a dashboard at the land grant universities (there are a total of 105 public and 7 private land grant institutions across the country, with at least one in every state (14)); local input regarding the needs and opportunities related to climate could be provided via the regional Extensions. Thus, via this dashboard, we can guide, and track, our progress at the National, State, and local levels in addressing the climate crisis.

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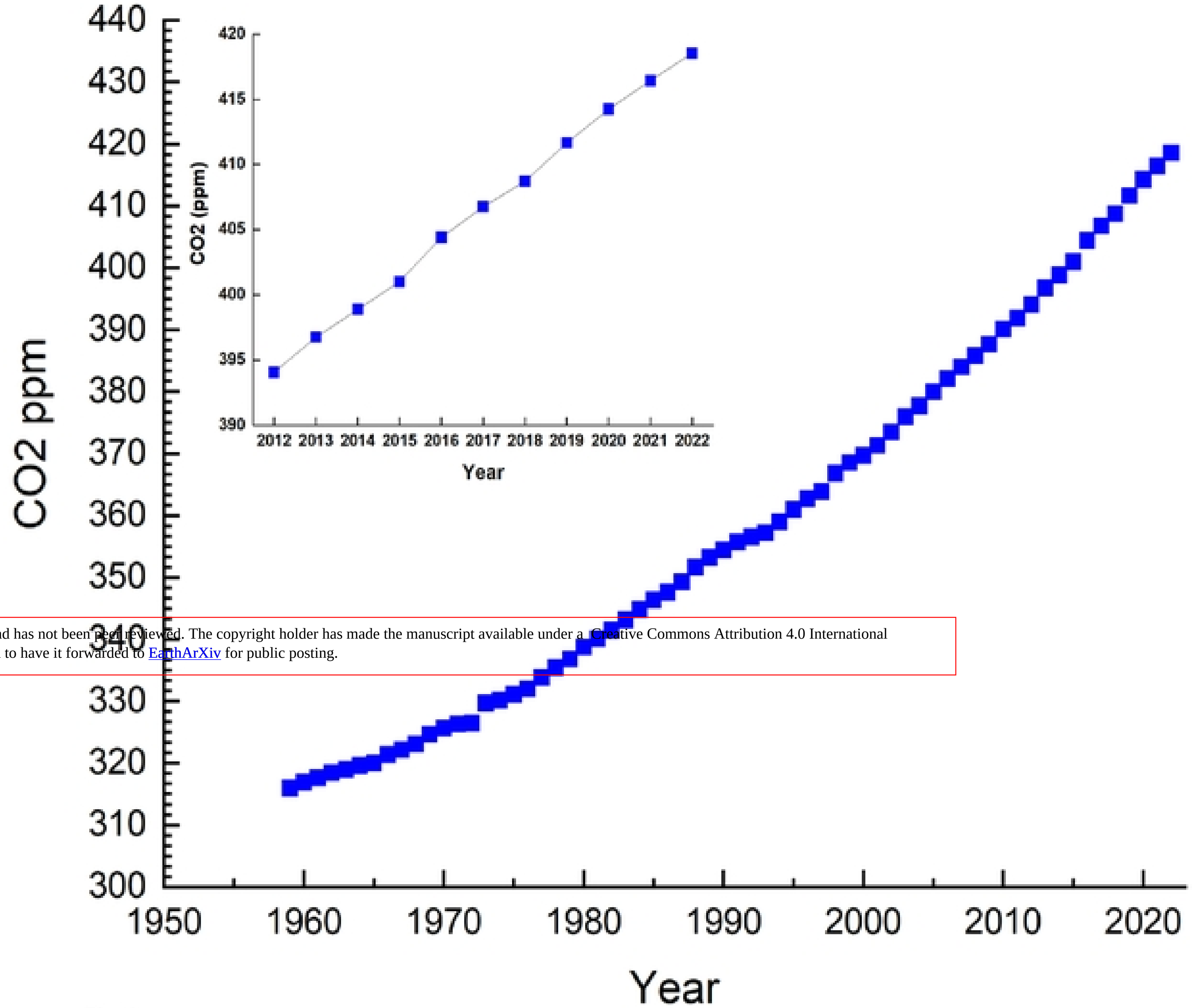

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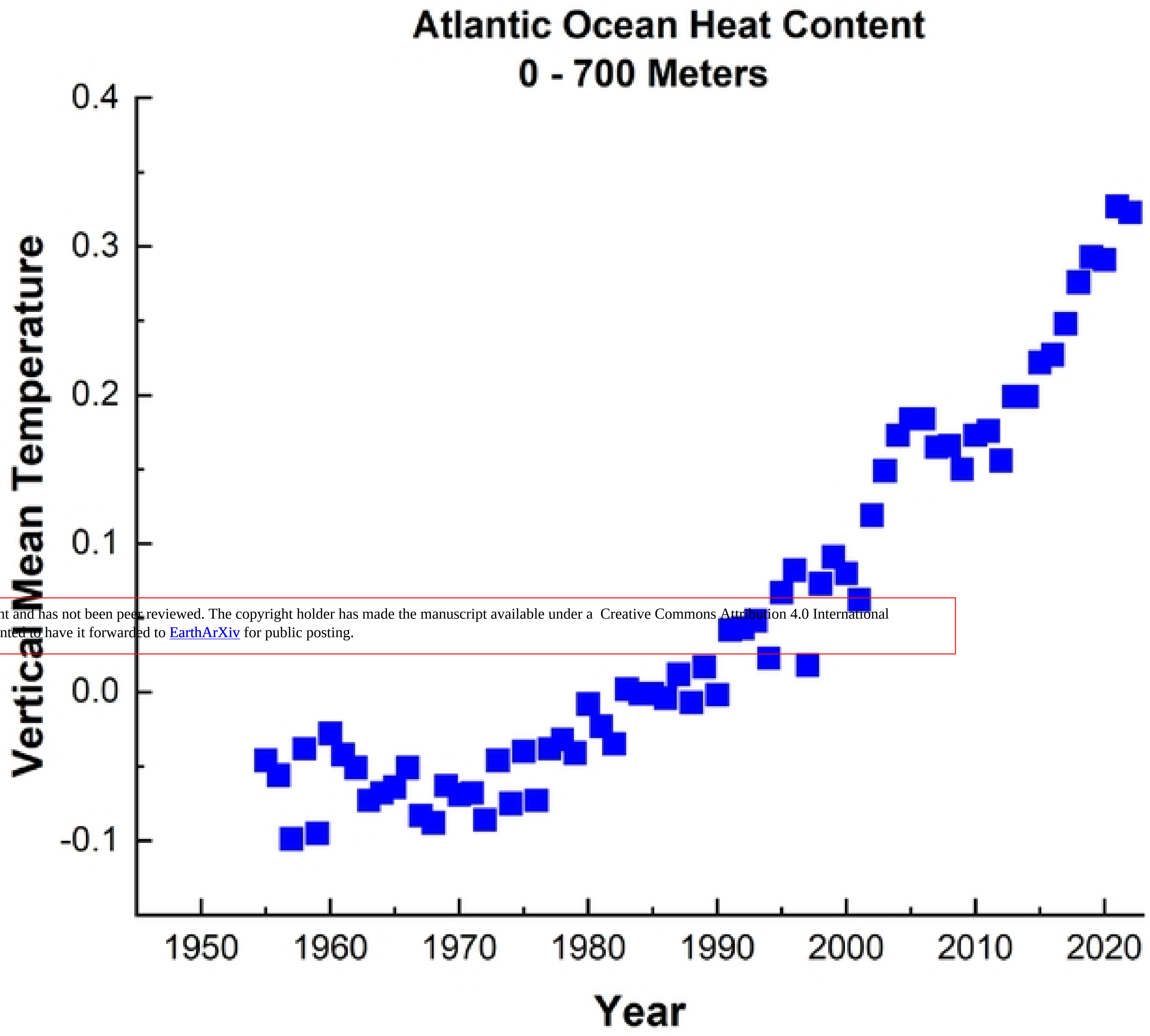

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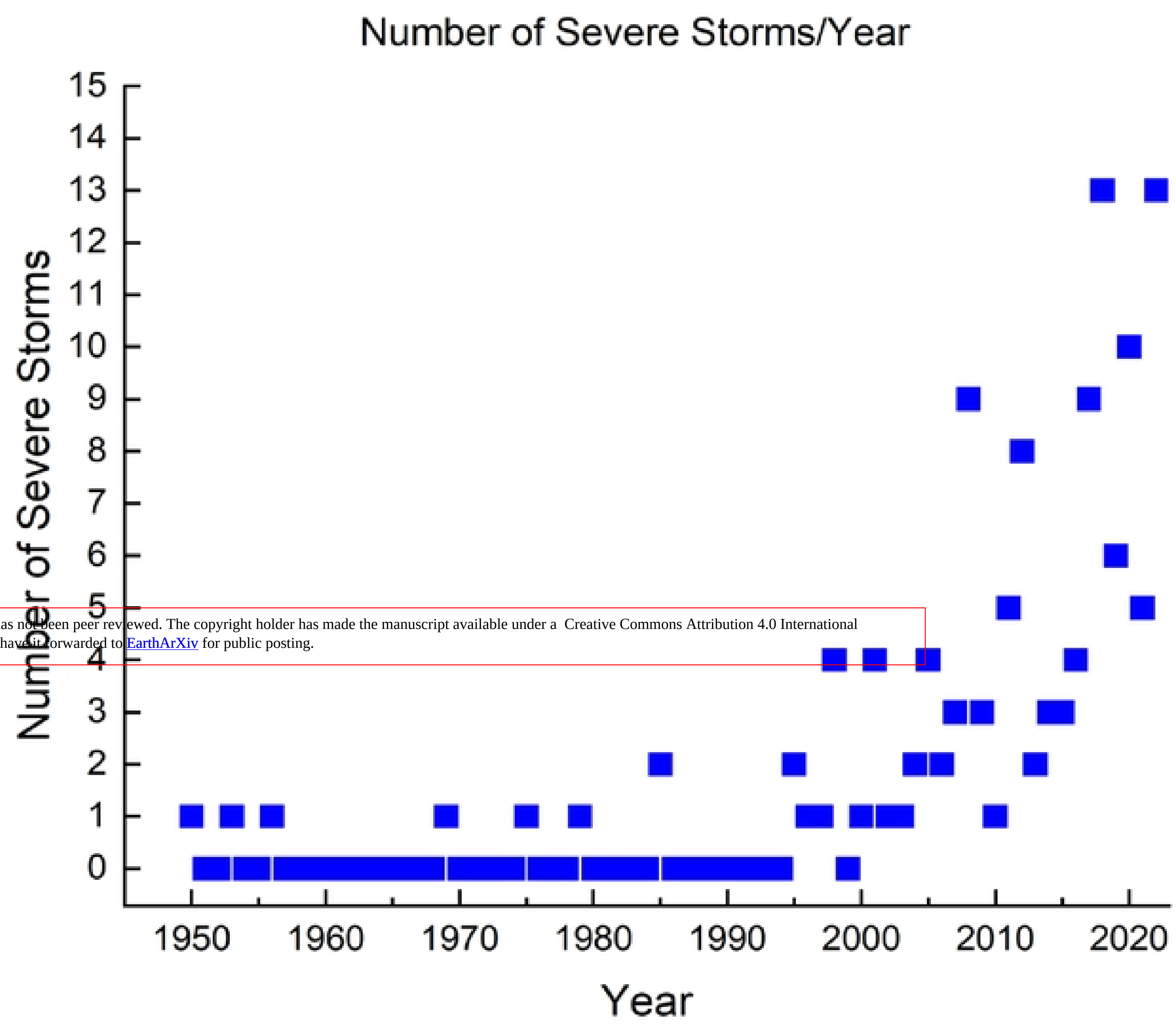

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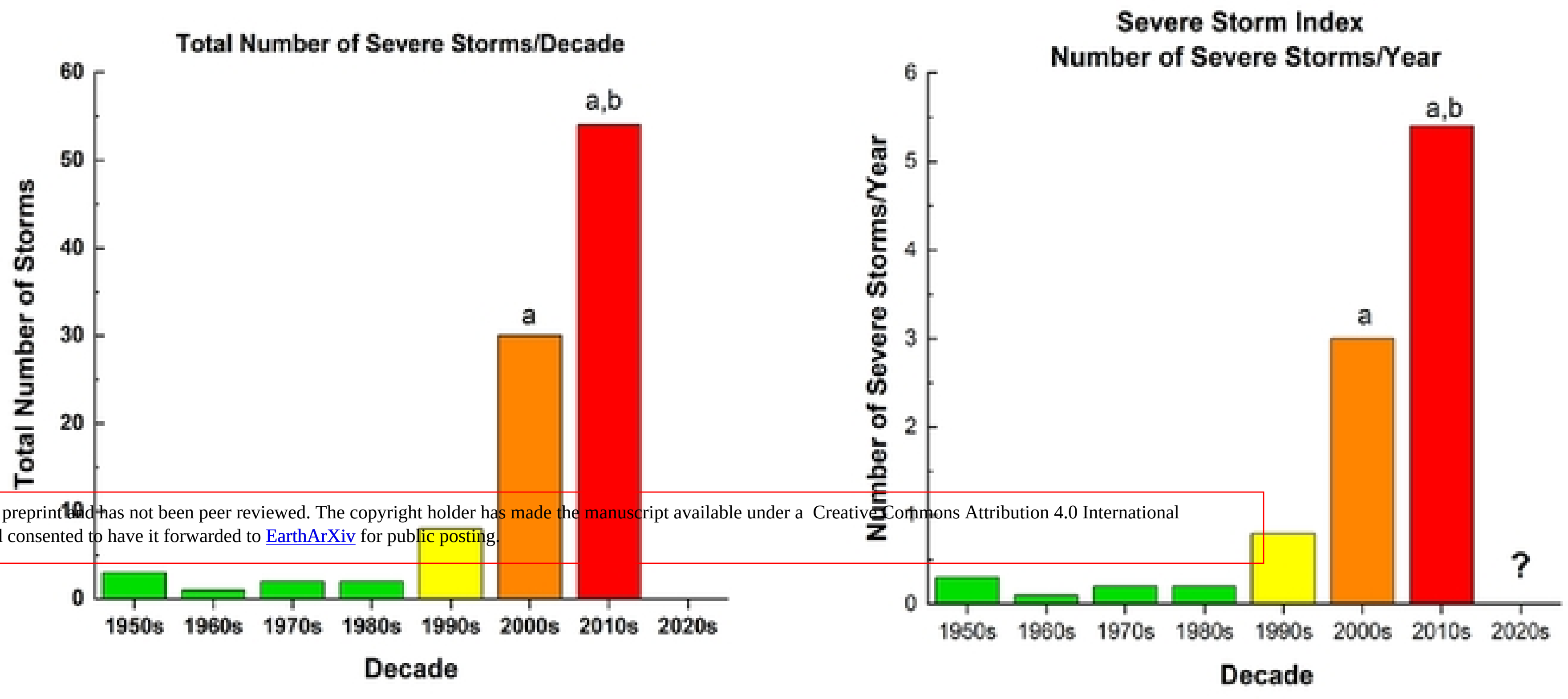

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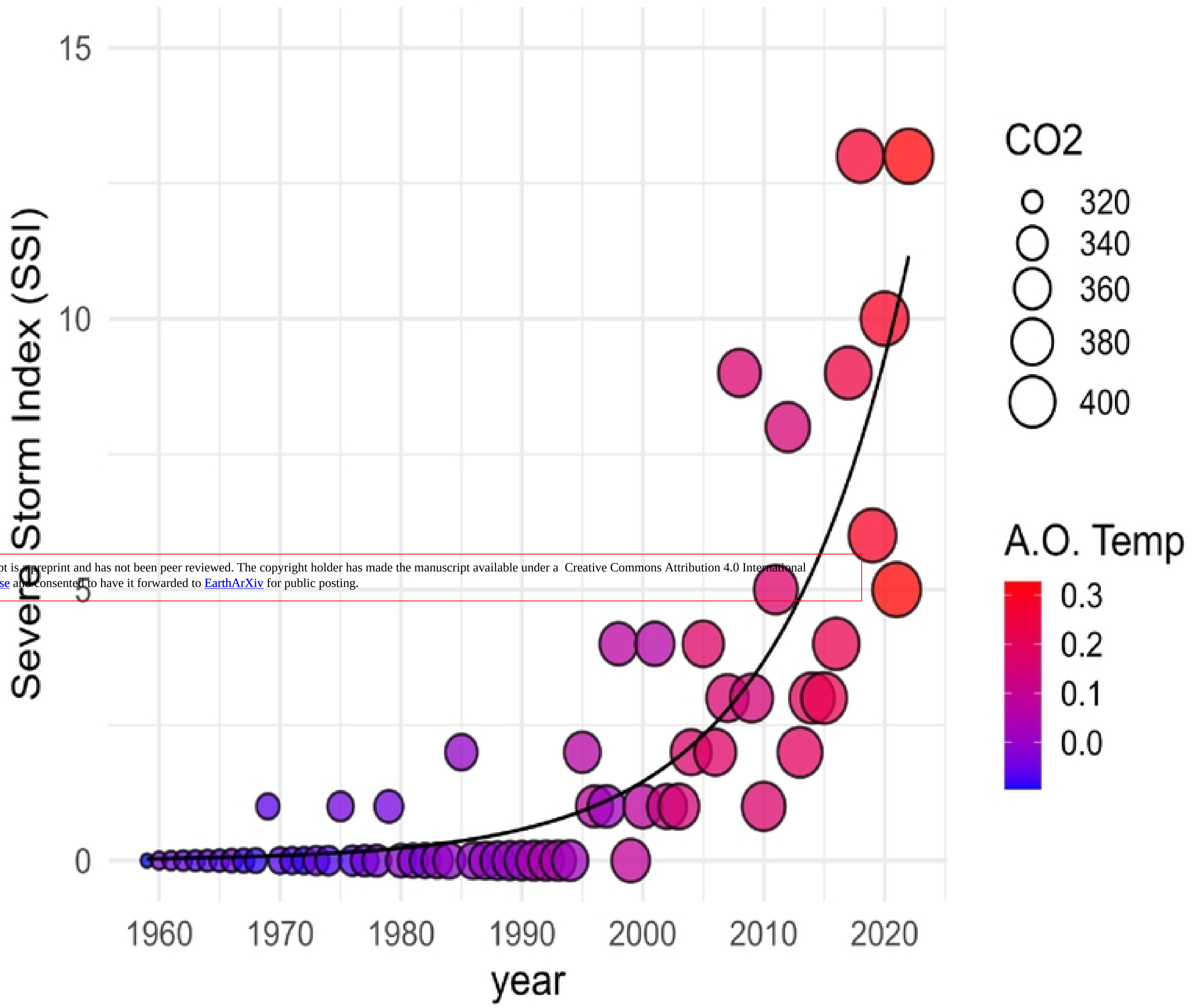

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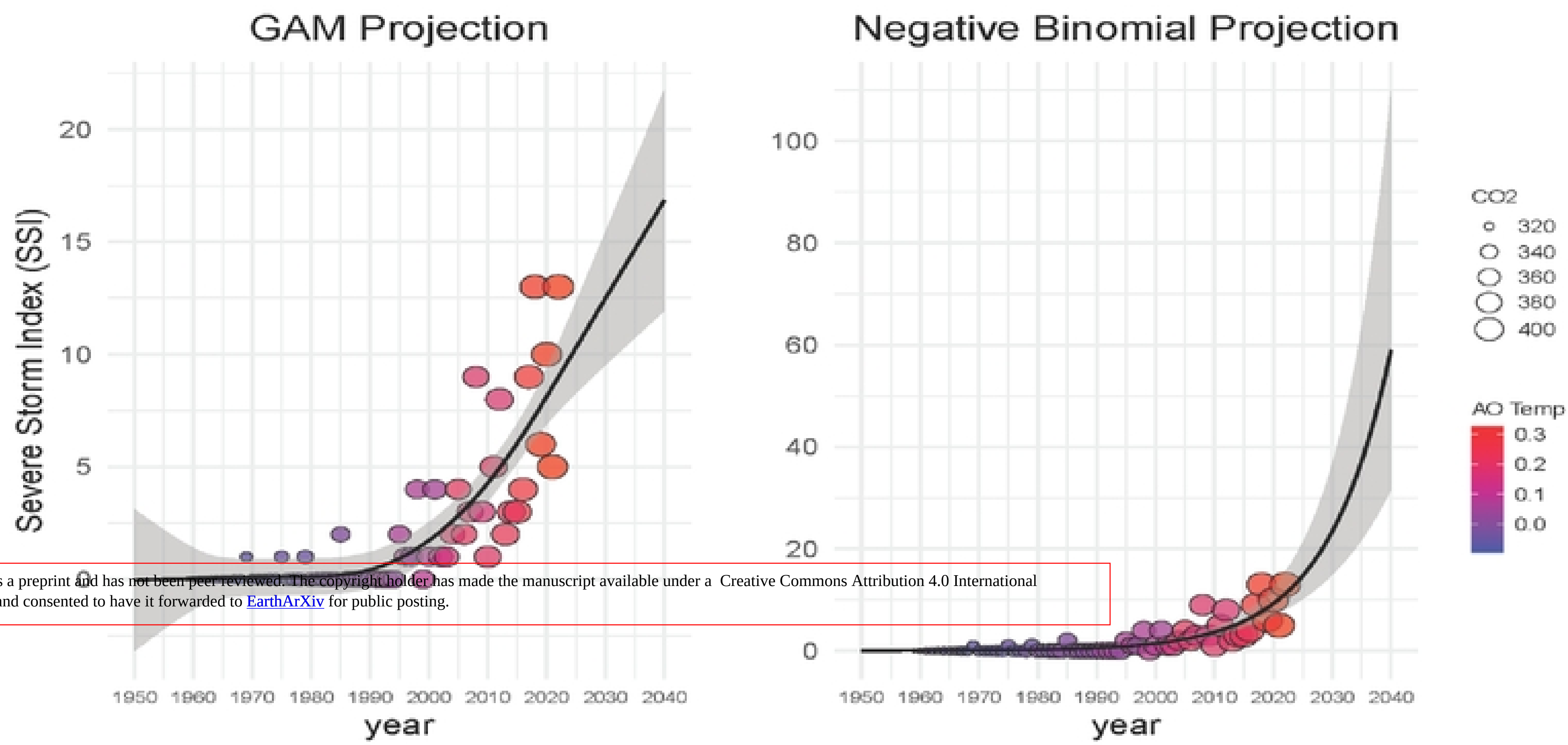
GAM Projection
Negative Binomial Projection
Severe Storm Index (SSI)
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CO2
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Figure 6