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ARTICLE

Is Climate Change Fuel to Increase Intense Tropical Cyclones in the North Indian Ocean?

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ABSTRACT

In recent years, severe cyclonic storm (SCS) activity is increased in the North Indian Ocean (NIO), particularly in the central Arabian Sea and Bay of Bengal. In the present study investigate the role of climate change on increasing intense severe cyclonic storms (Cat 4 & 5) at each 2.5° × 2.5° grid boxes in the NIO. Inter-governmental on Climate Change (IPCC) AR4 Model data sets for cyclone genesis parameters, sea surface temperature (SST) from Hadley Centre, cyclone tracks from Indian Meteorological Department and Joint Typhoon Warning Center during 1891–2010 is used. The study reveals stimulating results that the frequency of SCS increased during 1970–2010 (19) compared with 1891–1969 (12) at north of 15° N lat, but south of 15° N it is reversed in the Arabian Sea (AS) during southwest monsoon season(JJAS). In the Bay of Bengal (BoB) the scenario is reversed when compared with the Arabian Sea and the frequency of SCS was decreased in climate change environment. Strong latitudinal shift and increase the frequency of SCS is observed in the Arabian Sea during climate change scenario (1970–2010), but such phenomena is not noticed in the BoB. The main reason is reduction in vertical wind shear (easterly shear) along with increase in SSTs. To find out the relationship between the frequency of SCS and cyclone genesis parameters I did statistical tests, they also showed good results.

Keywords: Cyclone; Sea Surface Temperature; Vertical Wind Shear; Climate Change; Arabian Sea; Bay of Bengal

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1. Introduction

Tropical cyclone (TC) is one of the most deadly and destructive natural weather hazard on Earth, it causes huge damage to life, property, extreme rainfall and storm surges due to strong gale winds around the world in general and North Indian Ocean in particular [1–8]. Therefore, it is important to understand and estimation of climate change role on tropical cyclone in all ocean basins is crucial particularly in terms of their tracks, intensity, associated rainfall patterns and storm surge. Previous studies revealed that the large-scale ocean-atmosphere, in particular, high ocean temperature with a deep mixed layer, weak vertical wind shear (VWS) between 200 hPa and 850 hPa, high mid-tropospheric relative humidity may favour the rapid intensification of a TC [9–11]. Sea surface temperature play a vital role for the genesis of TC, and there is fact that SST > 26 °C is one of the criteria for the TC formation [12,13]. Cyclone activity was affect by the changes in sea surface temperature (SST).

A good estimation of tropical cyclone intensity and its identification helps in hazard management and mitigation planning, in quickly and on time. The genesis of cyclonic system, its intensification and dissipation is a synergistic process and it depends on a number of ocean-atmospheric variables such as sea surface temperature (SST), sea-air temperature contrast (turbulent heat fluxes), sea level pressure and mixing ratio. SST contributes strongly to strength surface wind speeds of the cyclone. This strong correlation is indicates the exchange of enthalpy process between the ocean and atmosphere due to this the cyclonic system is also called as natural Carnot engine. The higher the contrast is, the greater is the energy transferred upwards during cyclone genesis [14]. Due to rising ocean temperatures in the Northern Hemisphere more strong cyclones area developed compared with southern hemisphere. Climate models shows in a futuristic scenario of doubled CO_2, SST increases and the tropical oceans more prone to such intensification are the North Indian, the West Pacific and the Southeast Pacific basins.

The ocean plays a pivotal role on genesis and intensification through supply the energy in the form of latent heat flux and sensible heat flux to the tropical cyclone [15]. Strong warm sea surface temperatures, a decrease in easterly vertical wind shear and more ocean heat content in the Arabian Sea experience high tropical cyclogenesis [16–18].

Tropical ocean sea surface temperature is a key ingredient in deciding convective activity, the rate of evaporation and rainfall. According to Gray (1975) minimum 28 °C of sea surface temperature is one of the favorable conditions for genesis of the active convection in the tropical ocean basins [19]. Due to the global warming Arabian Sea getting warmer, these warm sea surface temperatures over the North Indian Ocean play a significant role in the genesis and intensification of tropical cyclone. Birth of tropical cyclone is more prevalent in the eastern AS region due to warmer SST compared to the western region. In recent years, it has been observed that more cyclogenesis occurs over this region as well due to rapid warming of the western AS [20]. During northeast monsoon season in association with strong sea surface temperatures and weak easterly vertical wind shear the number of extremely severe cyclones are increasing in the Arabian Sea basin [21]. Increase in emissions of sulphate and concentration of black carbon during premonsoon season along with a decrease in the easterly vertical wind shear contribute on recent increase in the strong cyclones in the Arabian Sea basin [8,22]. The Bay of Bengal and the Arabian Sea are the two arms of the Indian subcontinent with distinct ocean-atmospheric conditions. These two ocean basins experience seasonal reversal of winds, currents and formation of cyclones. Mohanty et al. [20] analyzed the tropical cyclones (TC) on global basis and their study revealed that about 7% of TCs are developed in the North Indian Ocean annually; it comprises the Arabian Sea (AS) and Bay of Bengal (BoB).

Generally, the Bay of Bengal more vulnerable to high frequency of cyclones compared with the Arabian Sea [22–25]. The Bay of Bengal (BoB) contributes significantly to approximately 70%–80%, whereas The Arabian Sea (AS) is 10%–20% of the total number of cyclones in the North Indian Ocean [26]. Although, in recent years the number of severe cyclonic storms in the Arabian Sea, particularly early and end of the cyclone season is increasing. More than 90% if very severe and super cyclones formed in the Arabian Sea end of pre-monsoon season, starting of Southwest and Northeast Monsoon [24].

Vertical Wind Shear (VWS) is considered one of the most key factors in cyclone intensity change. IT modifies the structure and precipitation distribution of the cyclone. VWS magnifies the dry mid-level air into the moist TC inner core [26]. In the North Indian Ocean seasonal VWS, westerly shear dominated with strong shear value in all three seasons (winter, pre-monsoon and post-monsoon), the highest easterly sheer magnitude is dominated in monsoon. For basin, weak easterly shear dominated in the Bay of Bengal during pre-monsoon and post monsoon seasons. Such phenomenon is the BoB is more favorable for the cyclone that the Arabian Sea during these seasons [27–29].

In the present study focused on two ingredients like sea surface temperature and vertical wind shear in a climate change scenario at each 2.5° × 2.5° grid boxes over the north Indian Ocean with the help of WCRP multi model database.

2. Materials and Methods

In the present study the following data sets are used.

Atmospheric winds: Monthly wind data at two different pressure level (850 and 200 hPa) obtained from WCRP multi model data base [5] for the vertical wind shear calculations. Vertical wind shear is the difference between U200 and U850. I downloaded the data from this website: https://catalogue.ceda.ac.uk/uuid/72afa18db5988d1be0066a26e09422df/.

Cyclone track: Tropical cyclone track data from Indian Meteorological Department and Joint Typhoon Warning Centre during 1891–2010. It contains the latitude and longitude position of tropical cyclone, Estimated Central Pressure (hPa) and Maximum Sustained Surface Wind (kt) at three-hour intervals. Tropical cyclone having maximum sustained wind speed of 90 kmph or more (severe cyclone storm stage) are included in the present study. According to Indian Meteorological Department (IMD) the weather disturbances are characterized based on the maximum sustained wind speed at every 3-min time interval (**Table 1**). I downloaded the data from this website: https://rsmcnewdelhi.imd.gov.in/report.php?internal_menu=MzM=.

Table 1. India Meteorological Department classification of atmospheric disturbances based on maximum sustained wind speed (kmph) in the North Indian Ocean.

Disturbance	Wind Speed in kmph
Low pressure area	<30
Depression (D)	30–50
Deep Depression (DD)	51–60
Cyclonic Storm (CS)	61–88
Severe Cyclonic Storm (SCS)	89–116
Very Severe Cyclonic Storm (VSCS)	117–166
Extremely Severe Cyclonic Storm (ESCS)	167–222
Super Cyclonic Storm (SuCS)	≥223

There are total 714 tropical cyclones with intensities exceeded 50 knots across the entire North Indian Ocean basin from 1891 to 2010. The frequency of severe cyclone storms in the Arabian Sea during two season is 227, whereas in the Bay of Bengal basin is 487.

Sea surface temperature: In addition, monthly SST data downloaded from U.K. Met office Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) datasets during 1891–2010 [30]. The SST anomaly calculated from the 1891–2010 mean climatology. I downloaded the data from this website: https://www.metoffice.gov.uk/hadobs/hadisst/.

In this study entire North Indian Ocean is divided into 2.5° latitudes (both Arabian Sea (AR1, AR2, AR, AR4, AR5, AR6, AR7 and AR8) and Bay of Bengal (BR1, BR2, BR3, BR4, BR, BR6, and BR7) with constant longitude for example AR1 is 50°–77.5° E, 22.5°–25° N (**Table 2**).

Table 2. Grid boxes in the North Indian Ocean.

	Arabian Sea Longitude	Latitude		Bay of Bengal Longitude	Latitude
AR1	50–77.5° E	22.5–25° N	BR1	77.5–97.5° E	20–22.5° N
AR2	50–77.5° E	20–22.5° N	BR2	77.5–97.5° E	17.5–20° N
AR3	50–77.5° E	17.5–20° N	BR3	77.5–97.5° E	15–17.5° N
AR4	50–77.5° E	15–17.5° N	BR4	77.5–97.5° E	12.5–15° N
AR5	50–77.5° E	12.5–15° N	BR5	77.5–97.5° E	10–12.5° N

Table 2. *Cont.*

	Arabian Sea Longitude	Latitude		Bay of Bengal Longitude	Latitude
AR6	50–77.5° E	10–12.5° N	BR6	77.5–97.5° E	7.5–10° N
AR7	50–77.5° E	7.5–10° N	BR7	77.5–97.5° E	5–7.5° N
AR8	50–77.5° E	5–7.5° N			

Student's t-test: In order to estimate trends in vertical wind shear, SST and cyclones, simple linear regression technique was used. These trends have been tested by using Student's t-test.

3. Results

The frequency of occurrence of severe cyclonic storms (SCS) during summer and post monsoon seasons in the two ocean basins of the North India Ocean is calculated at 2.5° × 2.5° and shown in **Figure 1**. It clearly shows that the frequency of SCS (23) is increased north of 15° N during summer monsoon season (JJAS) in a global warming period (1970–2010), in particularly between 17.5° N–20° N the frequency of occurrence is 50% of the total SCS, but in the Bay of Bengal it is at latitudes between 20° N–22.5° N. Recent observations also indicate the same phenomena (Ex. Gonu (2007), Phet (2010) cyclones) in the Arabian Sea. While the scenario is reversed during post monsoon (OND), the frequency of SCS increased south of 15° N. The percentage frequency of SCS is increased in both basins (AS – 30, BoB - 91) during warming period. In the Bay of Bengal, the situation is same; the frequency is increase north of the 15° N during summer and south of 150N in post monsoon season during warming scenario, but the increase is less compared with Arabian Sea during summer season and high in post monsoon season. During post monsoon season 12.5° N–15° N the frequency is more in both basins.

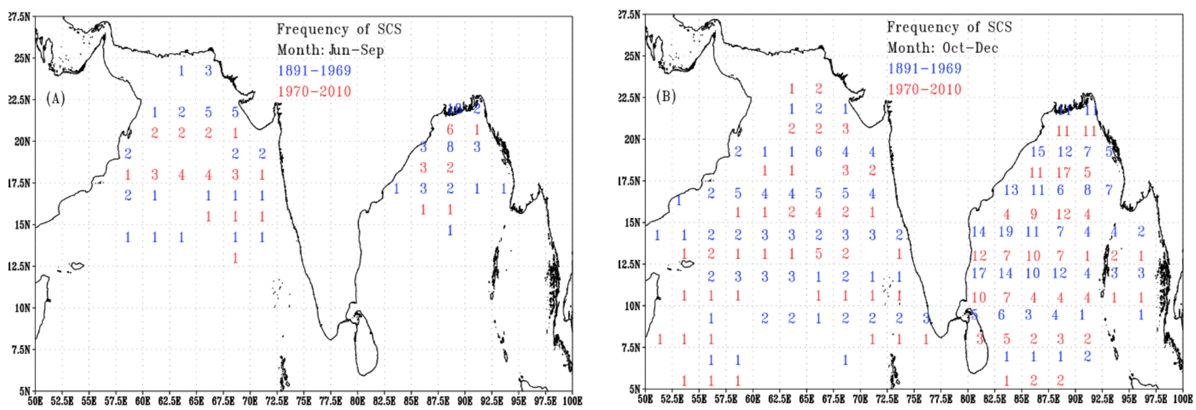

Figure 1. Severe Cyclonic Storm frequency. (**A**) Summer monsoon (JJAS) and (**B**) Post monsoon (OND). Blue and red colours represents the period 1891–1969 and 1970–2010 respectively.

Sea surface temperature (SST) anomaly at each latitudinal belt is averaged and depicted in **Figure 2**. In the Arabian Sea SST anomaly is strong positive at the north of 15° N it is about 0.15–0.25 °C during 1970–2010. The trend pattern is same to all the latitudes (increasing trend) but the strong correlation (0.41, significant at 0.01% level) with the frequency of SCS is at north latitudes. SST anomaly at the south of 15° N is also high but the relationship with cyclones is 0.31 which is significant at 0.01% level. In Bay of Bengal the strong positive SST anomaly (0.21–0.31) is observed at the south of 15° N during global warming scenario. The relation between SCS and SST anomaly is also strong in this place. Before the warming period both Arabian Sea and Bay of Bengal has a strong negative anomaly at all latitudinal belt.

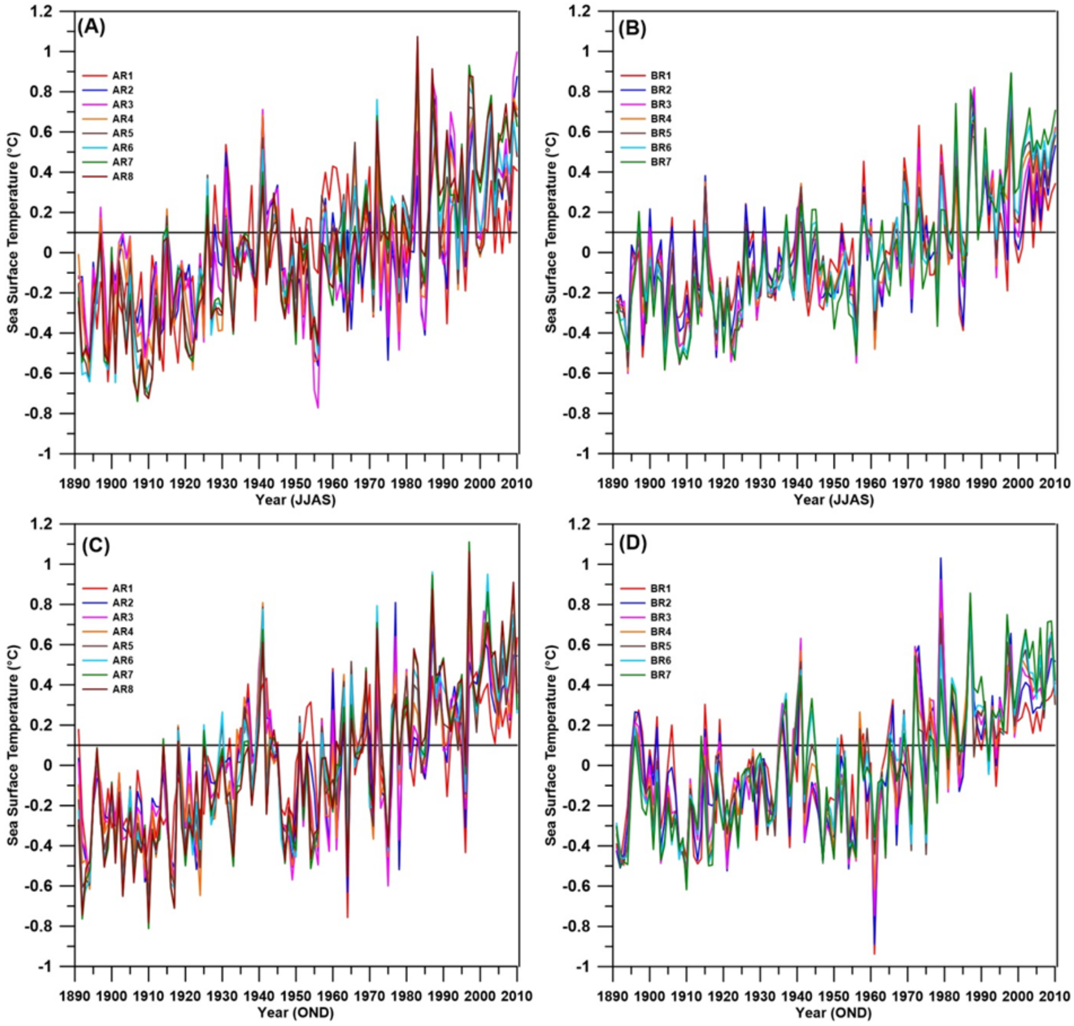

Figure 2. Latitudinal variation of sea surface temperature anomaly over the Arabian Sea (left panel) and Bay of Bengal (right panel) during summer and post monsoon season.

In the Arabian Sea AR1, AR2, AR3 and AR4 grid boxes shows very strong positive sea surface temperature anomaly in the recent decade when compared with the remaining grids during southwest monsoon (**Figure 2a**), particularly AR2 and AR3 regions are coincided with strong cyclones Gonu (2007) and Phet (2010). Very strong sea surface temperature anomaly (>1 °C) observed at AR6, AR7 and AR8 grid boxes in 1983 summer monsoon season and 1997 Northeast monsoon season (**Figure 2c**). In the Bay of Bengal all grid boxes except BR4 and BR5 shows >0.8 °C during 1998 southwest monsoon season (**Figure 2b**), and also a severe cyclonic storm formed at these grid boxes. During the northeast monsoon season grid boxes BR1 and BR2 have >0.9 °C in 1979 (**Figure 2d**). The Bay of Bengal is more warming in northeast monsoon particularly at the North of 15° N when compared with southwest monsoon season.

Environmental vertical wind shear modulates the intensity and structure of tropical cyclone. The vertical wind shear, defined by the zonal wind difference between two atmospheric pressure levels (200 hPa and 850 hPa), is averaged over the 2.5° latitude and constant longitude in the Arabian Sea (AR1...AR8) and Bay of Bengal (BR1…BR7) shown in **Figure 3** for the summer and post monsoon seasons. At north of 15° N shear is increasing trend and at the south, it is decreasing. Latitudinal variation in shear is more in the Arabian Sea compared with Bay of Bengal during summer monsoon season.

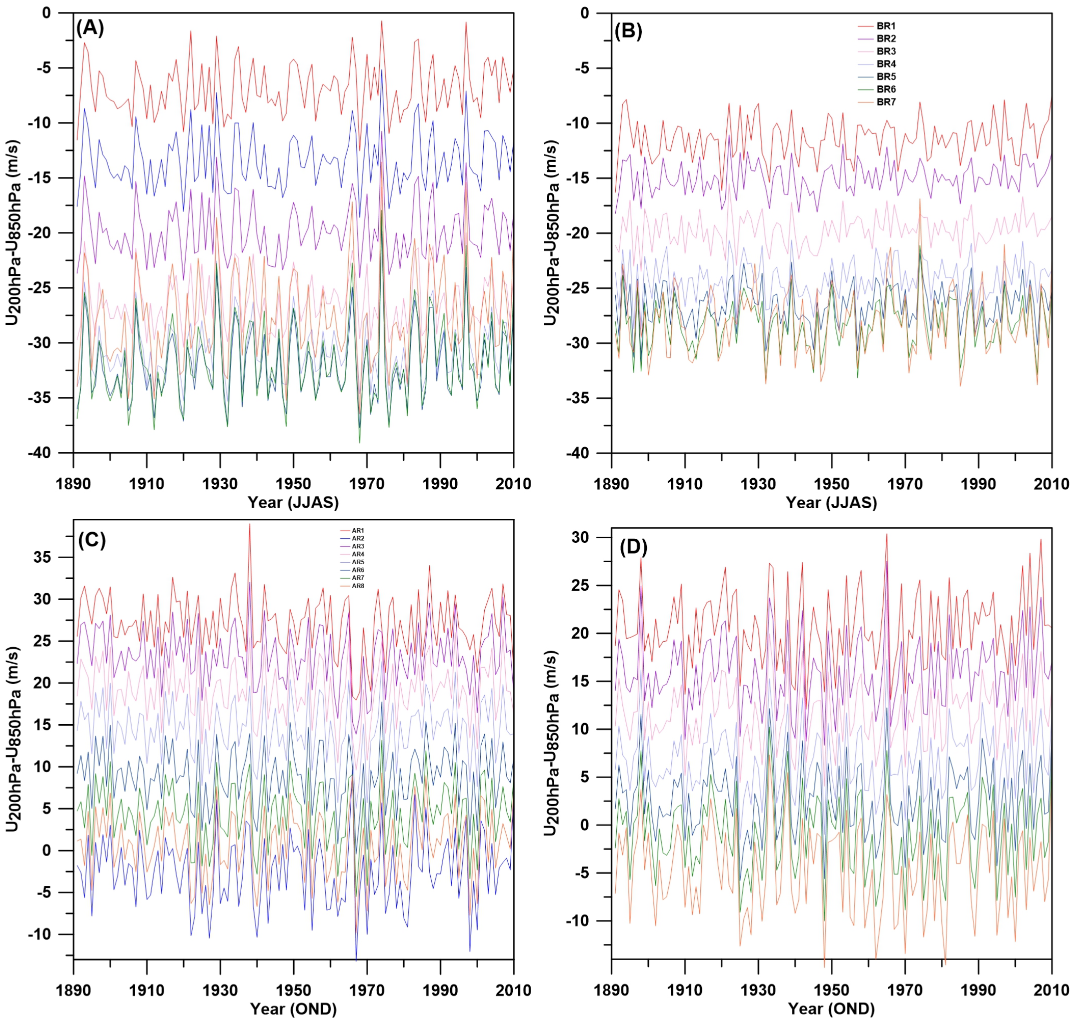

Figure 3. Latitudinal variation of Vertical Wind Shear over the Arabian sea (left panel) and Bay of Bengal (right panel) during summer and post monsoon season.

4. Discussion

The present study explores latitudinal changes of the IPCC AR4 model vertical wind shear and SST on increase of number of severe cyclonic storms in the North Indian Ocean. In the recent decades (1970–2010) the no of SCS increased in the AS when compared with the BoB during SW monsoon season (JJAS) and the increase is more at the central AS. During November and May the frequency of cyclones increasing in the north Indian Ocean and the intensification rate is also increased 20% per hundred years during November[31]. Previous studies also reported increase the frequency of SCS in the AS in global warming scenario[32–34] and the future climate RCP 4.5 projection scenario also reveal that the fourfold increase of the percentage of cyclones in the north Indian Ocean between 2081 and 2100 compared to 1986–2005[35] the projected changes of SSTs and wind shear is the responsible for the increase in SCS, it is also support the present study. Few studies have documented global sea surface temperature increases around 0.11 °C per decade since 1900, with an acceleration since the mid-20th century[34,35]. The present study also show a similar increasing trend, confirming the global warming impact on regional SST. Recent studies reported an increase in AS cyclones, especially during post monsoon season associated with decrease vertical shear, warming SSTs and rising ocean heat content[23,30].

5. Conclusions

The frequency of severe cyclonic storms in the Arabian Sea has registered increasing during summer monsoon north of the 15° N, but the Bay of Bengal shows opposite. The increasing trend has been primarily due to decrease in the vertical wind shear at a particular latitudinal belt. The sea surface temperature anomaly increasing trend also favours for the more number of SCS in the Arabian Sea. Arabian Sea is more warming in both monsoon seasons (southwest and northeast) when compared with Bay of Bengal. Thus, the future evolution of North Indian Ocean storm activity will critically depend on the warming of the sea surface waters (upto a depth of 60 m) and also the vertical wind shear. The stronger warming of North Indian Ocean (NIO) during recent years drove reduced vertical wind shear over the NIO and is thus responsible for the strong tropical cyclone activity observed. However, in addition to sea surface temperature (SST), other parameters—such as the vertical stability of the atmosphere, changes in the oceanic mixed layer depth and variations in ocean heat content—must also be considered in future projections of cyclonic activity over the North Indian Ocean.

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Not applicable.

Data Availability Statement

In the Data and Methodology section, I mention the website links for all data sets used in this study.

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Conflicts of Interest

The author declares no conflicts of interest relevant to the present study.

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