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Decade-low aerosol levels over the Bohai and Yellow Seas amid the COVID-19 lockdown

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ABSTRACT

Coronavirus disease 2019 (COVID-19) has crucially influenced anthropogenic activities, which in turn impacts upon the environment. In this study, we investigated the variations on aerosol optical depth (AOD) at 550 nm over the Bohai Sea and Yellow Sea during the COVID-19 lockdown (from February to March in 2020) of China mainland based on Moderate-resolution Imaging Spectroradiometer (MODIS) observation by comparing with historical AOD records (2011–2019). Our results show that with the lockdown implementation, the decade-low AOD levels are achieved in February and March 2020 (0.39 ± 0.18 and 0.37 ± 0.19, respectively), which are 22% and 28% (p < 0.01) lower than the average AOD between 2011 and 2019 (0.50 ± 0.08 and 0.52 ± 0.05, respectively). After the lockdown restrictions were relaxed and industrial production gradually resumed, the AOD in April 2020 rebounded to the historical average level. Besides, compared with historical observations (2011–2019), the AOD temporal variability from February to April 2020 showed different pattern, with the decade-high increase from March to April (+0.11) and decade-low increase from February to March (-0.01). Independent observations and simulation, including fine particulate matter (PM$_{2.5}$) from ground-based measurements, wind field from Cross-Calibrated Multi-Platform, satellite-derived aerosol type, and back trajectories calculation by Hybrid Single Paricle Lagrangian Integreated Trajectory (HYSPLIT) model, indicated that the above abnormal AOD variation can be attributed to reduction of anthropogenic emissions during the COVID-19 lockdown period. The results of this paper, therefore, indicate that aerosols over the Bohai and Yellow Seas are strongly influenced by human activities, and the public health events such as the epidemic may alter the intensity of human activities and thus the spatio-temporal pattern of aerosol over ocean. With the global spread of the epidemic and the corresponding significant changes in human behavior patterns (restrictions on human activities, etc.), more studies should be carried out in the future about the aerosol variability and its potential impact on the marine environment.

1. Introduction

Spread of Coronavirus disease 2019 (COVID-19) in 2020 had a remarkable influence on the global development and human lifestyles (Forster et al., 2020). In addition to the prevention and treatment of COVID-19 (Arellanos et al., 2021; Bakowski et al., 2021; Gharbharan et al., 2021; Wilson et al., 2021), many relevant studies have focused on the response of the natural environment to changes in human activity, including the impact on climate change (Forster et al., 2020; Rosenbloom & Markard, 2020), air quality (Bertram et al., 2021; Dhaka et al., 2020; Le Quéré et al., 2020; Le et al., 2020), water resources (Patni & Jindal, 2020; Selvam et al., 2020), water quality (Agarwal et al., 2020; Patterson et al., 2021; Xu et al., 2021; Yunus et al., 2020), marine environmental pollution caused by personal protective equipment (Akbarizadeh et al., 2021; Arduso et al., 2021; Cordova et al., 2021; De-la-Torre et al., 2021; Hartanto & Mayasari, 2021; Okuku et al.,

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1569-8432/© 2022 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
2. Data and method

2.1. Coronavirus disease 2019 in China mainland

Statistics on the epidemic in China mainland were obtained from the National Health Commission (https://www.nhc.gov.cn/). Fig. 1 summarizes the existing confirmed cases from January 20 to April 30, 2020. It can be seen that the distribution of existing confirmed cases of COVID-19 in China generally follows a normal distribution (Fig. 1). Specifically, the number of existing confirmed cases reached its peak on 17 February, with about 58,000 cases, and then began to decline. By 18 March, the number of new confirmed cases per day across the country fell to zero for the first time. By 26 April, inpatients cases dropped to zero in Wuhan, the number of existing confirmed cases reached its peak on 17 February, with a total of 31 provinces, autonomous regions (the Inner Mongolia, the Guangxi Zhuang, the Tibetan, the Ningxia Hui and the Xinjiang Uygur), and municipalities (Beijing, Tianjin, Shanghai and Chongqing) across the country taking similar actions in the following week, which launched the first-level response to this major public health emergency. During most of February (including the Chinese Spring Festival), transportation was stopped, all non-essential businesses and industries were shut down and all public activities were prohibited across the country. When the situation for epidemic prevention and control improved in late February and early March, traffic restrictions were gradually eased, and enterprises began to slowly resume production. In early April, the city of Wuhan, which was the first city in China that underwent lockdown, lifted its quarantine. Since then, all restrictions across the country have been removed and recovery in work and life has been fasten.

According to the epidemic evolution and prevention, February and March 2020 were regarded as lockdown period in this study.

2.2. Aerosol optical depth (AOD) data

The daily Moderate Resolution Imaging Spectroradiometer (MODIS) AOD dataset (MCD19A2) at 550 nm obtained from National Aeronautics and Space Administration (NASA) were used to investigate the AOD variation, with a spatial resolution of 1 km. This dataset is derived from the Multi-Angle Atmospheric Correction Algorithm (MAIAC) which performs aerosol retrievals based on a time series analysis and image-based processing (Lyapustin et al., 2011; Mhawish et al., 2019). Compared to traditional algorithms, it is characterized by improved cloud and snow detection (Lyapustin et al., 2018) and the cloud-polluted pixels removal (Lyapustin et al., 2012). MCD19A2 has been widely used in AOD studies and shown a good consistence with ground-based observations over coastal waters (Ettehadi Osgouei et al., 2022) and Chinese mainland (Zhang et al., 2019). The original AOD data was filtered by quality assurance flags.

Aerosol type dataset based on Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) obtained from NASA were used to analyze the characteristics of natural and anthropogenic aerosols.
2.3. PM response of AOD over the ocean to human activity changes.

over the Bohai Sea and Yellow Sea, and to reveal the causes for AOD changes in study area. This dataset has a vertical resolution of 30 m and a horizontal resolution of 333 m. In the latest version (Version 4), aerosols are divided into the following 8 types: Clean Continental, Dust, Elevated Smoke, Polluted Dust, Clean Marine, Polluted Continental/Smoke, Dusty Marine and not determined (Kim et al., 2018) in range of 0 to 30.1 km altitude. In this study, Polluted Continental, Elevated Smoke and Polluted Dust from 0 to 30.1 km altitude are regarded as anthropogenic aerosols; Clean Marine, Dusty Marine, Dust and Clean Continental from 0 to 30.1 km altitude are considered as natural aerosols (Tian et al., 2017).

To be consistent with the period of the epidemic’s development and the implementation of key quarantine measures, as described in Section 2.1 (Fig. 1), the AOD and CALIOP Vertical Feature Mask (VFM) products were analyzed for the period from January to April 2020. In addition, AOD products and CALIOP VFM products from 2011 to 2019 for the same period were compared with those in 2020. The difference between AOD in 2020 and that averaged from 2011 to 2019 is calculated to derive AOD anomaly.

The Bohai Sea and the Yellow Sea (Fig. 2) are adjacent to the China mainland. Under the influence of northerly or northwesterly winds between January and March every year, the aerosols in this area mainly come from the China mainland (Zhang et al., 2016). Therefore, the Bohai Sea and Yellow Sea were selected as the study area to analyze the response of AOD over the ocean to human activity changes.

2.3. PM$_{2.5}$ concentration data over the Chinese mainland

Data of fine particulate matter (PM$_{2.5}$) concentrations from 2015 to 2019 were provided by China National Environmental Monitoring Centre (https://www.cnemc.cn) and used to characterize the aerosols emitted by human activities. As aerosols over the study area are mainly affected by those over the northern and central-eastern Chinese mainland (Zhang et al., 2016), data of PM$_{2.5}$ concentrations from 644 monitoring sites in those regions were selected to analyze the effects of changes in human activities.

To reflect the difference in PM$_{2.5}$ concentration between 2020 and previous years (2015–2019) for the same months, the relative changes (RC) were calculated by following equation:

$$RC = \frac{PM_{2.5}(2020) - PM_{2.5}(2015 \sim 2019)}{PM_{2.5}(2015 \sim 2019)} \times 100\%$$  \hspace{1cm} (1)

where PM$_{2.5}$(2020) is PM$_{2.5}$ concentration in 2020 and PM$_{2.5}$(2015 ~ 2019) is that averaged from 2015 to 2019.

Fig. 3 shows the distribution of PM$_{2.5}$ concentrations in northern and central-eastern China from January to April 2015 to 2020. In January 2020, human activity was unaffected by the epidemic due to the fact that the strict restrictions over the country began on 30 January, with PM$_{2.5}$ concentrations during that month averaged for the whole area (84.4 ± 34.4 g/m$^3$) being comparable to the same period between 2015 and 2019 (only 0.9% lower than the average for the same period between 2015 and 2019).

In contrast to PM$_{2.5}$ concentrations in February and March between 2015 and 2019 (65.4 ± 19.9 g/m$^3$ and 55.2 ± 13.2 g/m$^3$, respectively), these in February and March 2020 were reduced to their lowest values for the previous 6 years (47.3 ± 14.6 g/m$^3$ and 36.8 ± 9.34 g/m$^3$, respectively) due to the imposed restrictions, a decrease of about 28% (p < 0.01) and 33% (p < 0.01), respectively.

 lique with preliminary control of epidemic and recovery in work and life activities, PM$_{2.5}$ levels (about 39.1 ± 14.2 g/m$^3$) increased compared with that in March 2020, due to anthropogenic emissions as well as secondary particulate production (Nichol et al., 2020).

2.4. Wind field data over the sea

The monthly Cross-Calibrated Multi-Platform (CCMP) Ocean Surface Wind Vectors data was provided by the Remote Sensing System (http://data.remss.com/ccmp/), with a spatial resolution of 0.25° (Carvalho et al., 2014). This data was used to analyze the sources of maritime aerosols from January to April 2011 to 2020.

As seen in Fig. 4(a-d), the study area was dominated by northerly or northwesterly winds in January and February 2020 (Fig. 4 a, b) and northwesterly or westerly winds in March and April 2020 (Fig. 4 c, d). The wind field for January to April 2020 is consistent with that for these months between 2011 and 2019, as indicated by the fact that the average wind field from 2011 to 2019 (blue arrows in Fig. 4 e-h) is highly consistent with that from 2011 to 2020 (red arrows in Fig. 4 e-h).

2.5. Back trajectories simulation

The Hybrid Single Paricle Lagrangian Intergrated Trajectory (HYSPLIT) model, which is widely used in atmospheric pollutant transport analysis (Bogawski et al., 2019; dos Santos & Hoinaski, 2021), is adopted to calculate air mass trajectories. Specifically, 48 h back trajectories (00, 06, 12 and 18 UTC) at 500 m height were generated every hour to identify the potential sources of air mass in study area.

Fig. 2. (left) Location of the study area (the red rectangle denotes the Bohai Sea and Yellow Sea). (right) Details of the study area. The data presented is the AOD level averaged over March 2020 (white area is region without valid observations). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 3. PM$_{2.5}$ concentration between January and April 2020 (a-d) and the averages between 2015 and 2019 (e-h) over the central-eastern China mainland.

Fig. 4. Sea surface wind fields from January to April in 2020 (a-d) and the equivalent multi-year averages (e-h) (red arrows in the e-h panels represent the averages from 2011 to 2019; blue arrows represent the averages from 2011 to 2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Meteorological data with a resolution of 1° from Global Data Assimilation System (GDAS) during January to April from 2011 to 2020 were used as model input.

Air mass trajectories (Fig. 5a ~ b) show that a majority (98.96% and 75%, respectively) of air masses come from the northwest in January and February 2020 over the study area. Although there also exists the air masses from the southwest and northeast, air masses originated from northwest still (79.04% and 58.34% respectively, Fig. 5c ~ d) dominated the study area in March and April 2020. The trajectories between 2015 and 2019 (Fig. 5e ~ h) is consistent with that during the same period in 2020.

2.6. Methodology

The data were analyzed with the following steps.

1. The regionally averaged monthly satellite AOD levels (MCD19A2) from January to April in 2020 were compared with those in same periods from 2011 to 2019, with the emphasis on the lockdown effect during February and March.

2. Spatial characteristic of AOD anomaly during January to April in 2020 was analyzed, which was calculated as the difference in each image pixel between monthly AOD in 2020 and that averaged from 2011 to 2019.

3. For the mechanism analysis, firstly, the monthly wind field from satellite observations and back trajectories simulation of air masses were used to illustrate the possible aerosol sources over study area. Secondly, the land-based monthly PM$_{2.5}$ concentration observation over the possible aerosol sources was used to analyzed the main reason of AOD abnormal variation in 2020, which was further confirmed by independent CALIOP-derived aerosol type.

3. Results

3.1. Temporal variation of AOD

Fig. 6 shows the monthly AOD over the Bohai Sea and Yellow Sea, the northern and central-eastern China mainland from January to April 2011 to 2020. In terms of AOD levels (Fig. 6a), there were no obvious differences in January and April 2020 compared with the same periods from 2011 to 2019, while there were significant changes observed between February and March 2020 and the same months from 2011 to 2019. Specifically, the AOD level is lowest in February 2020 (0.39 ± 0.18), which is 22% (p < 0.01) lower than the average AOD in February between 2011 and 2019 (0.50 ± 0.08, Fig. 6a-b). In March 2020, the AOD level decreased further, resulting in a lowest AOD level (0.37 ± 0.19) in nearly a decade, which was 28% (p < 0.01, Fig. 6b) lower than the average AOD in March between 2011 and 2019 (0.52 ± 0.05, Fig. 6a-b). This reduction in AOD over the study area for February and March (about 22% and 28%, respectively) was consistent with the observed decreases in AOD level (30% and 33%, Fig. 6c) and PM$_{2.5}$ concentration (28% and 33%, Fig. 3) over the east-central China region during the corresponding months.

Fig. 5. 48 h back trajectories from January to April in 2020 (a-d) and the equivalent ones from 2015 to 2019 (e-h). The numbers in different color represent the percentages of air masses from directions.
and March 2020 accounted for 80% and 95% of the whole study area, respectively (the blue area over the sea in Fig. 7). At the same time (February to March 2020), the significant negative AOD anomalies (-0.16 ± 0.09 and -0.17 ± 0.06) in the central-eastern China mainland were found and the areas that show negative AOD anomalies in February and March 2020 accounted for 86% and 98% of the whole study area, respectively (the blue area over the China mainland in Fig. 7), which is in agreement with the PM$_{2.5}$ change shown in Fig. 3 (b) and (c).

4. Discussion

4.1. Mechanism behind AOD abnormalities from February to March 2020

The reduction in atmospheric particulate matter concentrations associated with human activities over the China mainland caused by lockdown during the period from February to March 2020 was the main reason for the reduced AOD in the Bohai Sea and Yellow Sea. The wind field data and back trajectories over the sea surface (Fig. 4 b, c and Fig. 5 b, c) show that the Bohai Sea and Yellow Sea were dominated by air mass originated from northwest in February and March 2020. Under the influence of above driving forces, aerosols in the study area are dominated by land-based sources. Due to the impact of the epidemic, transportation was curtailed, all non-essential businesses were shut down, and all public activities were prohibited across the China mainland during February and March 2020, resulting in the atmospheric particulate matter concentrations decreasing (Fig. 3 b, c). Compared with February and March between 2015 and 2019, the PM$_{2.5}$ concentrations across the China mainland decreased by about 28% ($p < 0.01$) and 33% ($p < 0.01$) in February and March 2020, respectively, which resulted in lower AOD levels over the study area at this time compared to previous years (Fig. 6).

Independent observations of the aerosol type variation based on the CALIPO VFM products over the Bohai Sea and Yellow Seas during January to April from 2011 to 2020 further proved the above analysis (Fig. 8). Fig. 8 shows that the variation of anthropogenic aerosol frequency is consistent with the AOD changes over study area. Specifically, the proportion of anthropogenic aerosol during the COVID-19 imposed lockdown (February to March 2020) was 27% and 28% lower than the same period during 2011 to 2019 (Fig. 8 a), while the proportion of natural aerosol has no significant changes (Fig. 8 b).

4.2. Comparison with previous studies

To control the spread of the epidemic, many countries around the world implemented lockdown in 2020, which effectively restricted human activities over the short term. Changes in the atmospheric environment were reported during these lockdown periods at global, regional, and national scales, covering different parameters such as AOD, PM$_{2.5}$, NO$_2$, CO, SO$_2$, and O$_3$ (Lal et al., 2020; Rodriguez-urrego & Rodriguez-urrego, 2020; Sanap, 2021).

Although most of these studies focused on the atmosphere over land, these results are comparable and consistent with the our result over seas. Specifically, the concentration of atmospheric pollutants decreased
considerably during the lockdown periods, which was mainly attributed to the reduction of pollutant emissions due to limited human activity. For example, Dang et al. (2021) showed that air pollutant concentrations over land decreased in more than 160 countries or regions worldwide as a result of the lockdown, with NO\textsubscript{2} and PM\textsubscript{2.5} concentrations decreasing by approximately 4% to 5% compared to the same period in previous recent years. Studies in China have also shown that concentrations of key air pollutants such as PM\textsubscript{2.5} and NO\textsubscript{2} were greatly reduced in most areas during the lockdown (Chen et al., 2020; He et al., 2020; Yumin et al., 2021), with more pronounced reductions observed around more economically developed regions, such as BTH (Beijing-Tianjin-Hebei) region (Bao & Zhang, 2020; Nichol et al., 2020), Triangle of Central China (Yin et al., 2021), Yangtze River Delta (Li et al., 2020; Wang et al., 2021; Yuan et al., 2021) as well as Pearl River Delta (Wang et al., 2021). Similar studies have been reported in India (Lokhandwala & Gautam, 2020; Naqvi et al., 2021), Poland (Filonczyk et al., 2020), Mexico (Fu et al., 2020), Austria (Lovri´c et al., 2021), and Florida (El-Sayed et al., 2021). For example, during the strict restrictions period in India, NO\textsubscript{2}, PM\textsubscript{2.5} and AOD all decreased by varying degrees compared to the same period in previous years, especially in metropolitan areas such as New Delhi, Mumbai, Bangalore, and Kolkata (Ranjan et al., 2020; Singh et al., 2020; Vega et al., 2021; Yadav et al., 2020). All these above results are consistent with this study, which showed a notable decrease in AOD over the ocean during the lockdown.

After the easing of the lockdown, atmospheric pollutant concentrations rebounded in most areas. Ropkins et al. (2021) showed that NO and NO\textsubscript{2} concentrations in the United Kingdom decreased by approximately 32% to 50% during the restrictions period compared with the pre-lockdown period, but when the quarantine was lifted, their concentrations rose by about 33% as vehicles returned to the roads. Wang et al. (2020) showed that when the control measures were eased in China, the concentration of air pollutants increased to some extent compared with the lockdown periods, as transportation and industry were allowed to resume. As the restrictions were lifted, concentrations of major air pollutants such as NO, NO\textsubscript{2}, and SO\textsubscript{2} increased by about two to three times in southwest China (Chen et al., 2020). These results are in consistency with the observed rapid increase of AOD over the ocean after the restrictions were removed.

Although the characteristics of AOD variation over the Bohai Sea and Yellow Sea observed in our study during the period of lockdown are similar as that over the terrestrial atmosphere revealed by previous studies, the mechanisms of observed changes are different. The reduction of terrestrial air pollutants is a direct result of decreased anthropogenic aerosol emissions by limiting human activities over land. The decrease in maritime AOD is an indirect result of the reduction of terrestrial anthropogenic aerosol emissions during the lockdown, that is, anthropogenic aerosol was transported to the study area by the wind. Therefore, it can be seen that the aerosol emitted by human activities not only affect the local atmospheric environment, but also have a remarkable influence on the maritime atmospheric environment of the surrounding area through atmospheric movement.

### 4.3. Future work

Although the epidemic has lasted for more than two years, it has not been effectively controlled globally. In order to avoid the global spread of COVID-19, human behavior patterns have changed to some extent (restrictions on human activities, the requirement of wearing protective masks, etc.). Therefore, more studies should be carried out in the near future about the atmosphere environment variability including AOD, aerosol profile and type, and atmospheric pollutant emissions concentration, as well as its potential impact on the marine environment, including photosynthetically active radiation (PAR) and marine primary productivity.

PAR is a key factor controlling ecological processes (Jonard et al., 2020; Wu et al., 2019). PAR on the ocean controls the growth of phytoplankton to some extent, which in turn affects the ocean primary productivity (Falkowski et al., 1998; Vallina et al., 2014). The AOD can directly affect PAR (Eswaran et al., 2019; Obregon et al., 2020). For instance, Tripathy et al. (2014) showed that in the Arabian Sea, an increase in urban aerosol concentrations can cause a 44% reduction in PAR. Therefore, the impact of changes in AOD due to the lockdown on PAR and marine productivity should be investigated further.

Aerosols also provide nutrients to the ocean through deposition, which in turn affects marine ecosystem (Johnson et al., 2010). Studies have shown a correlation between aerosol deposition and marine primary productivity (e.g., Meskhidze et al., 2007; Shi et al., 2012; Tan et al., 2014; Yoon et al., 2017). In recent years, the impact of anthropogenic aerosols has attracted widespread attention (e.g., Conway et al., 2019; Hamilton et al., 2020; Huang et al., 2015) where it has been shown that anthropogenic aerosols mixing with dust aerosols can form nutrients which affect marine phytoplankton growth through deposition (Shi et al., 2012). For example, the strong dust and polluted aerosol deposition from March 12 to 17, 2015 resulted in 50% higher chlorophyll concentration in the subarctic Pacific Ocean than before the dust deposition (Luo et al., 2020). Therefore, variations in aerosol concentrations and types due to changes in human activity during the lockdown and the resulting impact on marine primary productivity should be studied.
5. Conclusion

The COVID-19 epidemic broke out in China in January 2020 and gradually receded there in April 2020. During this period, China experienced a series of restrictions and lockdown, followed by the gradual easing of these conditions, which caused notable changes in maritime AOD levels. In the present study, the abnormal changes in the AOD levels over the Bohai Sea and Yellow Sea during the period of COVID-19-imposed lockdown were investigated by comparing these levels with those during the same months for 2011 to 2019 based on the satellite observations. The main reasons of AOD abnormal changes were then revealed by combining the measured PM$_{2.5}$ concentration, satellite-derived aerosol type, wind field dataset and back trajectories simulation. Our results show that the clearest atmospheric environment for the recent decade was found in February and March 2020 compared to same months, which was mainly caused by changes in human activities during the lockdown. The main conclusions of this paper are, therefore, as follows.

(1) With the implementation of lockdown, the AOD levels in February and March 2020 dropped to their lowest values (0.39 ± 0.18 and 0.37 ± 0.19, respectively) for the last decade, which was 22% (p < 0.01) and 28% (p < 0.01) lower than the averaged AOD values in February and March between 2011 and 2019 (0.50 ± 0.08 and 0.52 ± 0.05, respectively).

(2) In April 2020, after the restrictions were relaxed and industrial production was resumed gradually, the AOD levels over the Bohai Sea and Yellow Sea rebounded rapidly to the average AOD levels seen between 2011 and 2019 (AOD anomaly is −0.02 ± 0.13).

(3) The temporal variation of AOD showing a decrease followed by an increase from February to April 2020 is opposite with that from 2011 to 2019. The AOD increase from February to March 2020 was lowest over the last decade with a value of −0.01, while highest from March to April 2020 with a value of 0.11.

(4) The result of PM$_{2.5}$ wind filed, back trajectories and aerosol type data showed that the abnormal variation of AOD over the Bohai Sea and Yellow Sea was mainly caused by reduction of anthropogenic aerosol emission during the COVID-19 imposed lockdown.

(5) The results of this paper indicate that maritime aerosols are strongly influenced by human activities. Changes of human activity within the context of extreme events such as the COVID-19 pandemic can significantly affect the marine environment, especially coastal waters. With the global spread of the epidemic, more studies should be performed about the impact on the marine environment in the future.

CRediT authorship contribution statement

A. Runa: Methodology, Writing – original draft. Tingwei Cui: Conceptualization, Supervision. Song Qing: Writing – review & editing. Ting Wei: Bing Mu: Software. Yanfeng Xiao: Visualization. Yanlong Chen: Validation. Yuhai Bao: Jie Zhang: 

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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