Synoptic and meteorological drivers of regional ozone pollution events in China

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Abstract

Surface ozone (O₃) pollution events are becoming more frequent and have recently emerged as a severe air pollution problem in China. However, the spatial–temporal distribution of surface O₃, as well as its primary synoptic and meteorological drivers, remains poorly understood. The purpose of this study was to identify the key synoptic and meteorological drivers of O₃ pollution in different regions of China. To achieve this goal, this study established meteorology overlaps of regional O₃ pollution events in space and time and applied a comprehensive statistical model selection method for optimal synoptic and meteorological models, based on a newly released O₃ dataset for 2015–2018. It was observed that extreme regional O₃ pollution events (duration > 7 d) occurred more frequently and exhibited a high co-occurrence frequency (> 50%) with air stagnation (AS). Moreover, the beginning and end of 69% of the regional O₃ pollution events coincided with regional daily maximum temperature changes. The intensity of AS is the dominant driver of O₃ pollution event intensity across most of the six selected megacity regions. Although other meteorological drivers, such as the intensity of hot days (HD) and meridional wind of 10 m were also important, their impacts varied according to the region. Overall, increase in extreme AS and HD led to the worsening of regional O₃ pollution events. These findings imply that mitigating regional O₃ pollution should consider changing synoptic and meteorological conditions.

1. Introduction

Surface ozone (O₃) adversely affects human health, especially when its concentration is > 100 μg m⁻³ (World Health Organization 2018). In recent decades, China has become an epicenter for O₃ pollution (Zhang et al 2016). Since 2013, annual O₃ pollution days when O₃ concentrations above a certain threshold have been increasing in many Chinese cities (Wang et al 2017, Gong and Liao 2019). However, regional Chinese O₃ pollution events and their synoptic and meteorological drivers have remained poorly understood due to limited O₃ observational data availability, leading to a lack of reliable quantification (Zhao et al 2009). Understanding dominant O₃ event drivers is necessary to establish effective O₃ pollution event mitigation strategies.

Local meteorological variables, such as temperature (Bloomer et al 2009) and solar radiation flux (Otero et al 2016, Wang et al 2017), can lead to severe O₃ pollution by enhancing the associated photochemical reaction rate. Temperature has been found to be one of the most likely variables to increase the summer maximum daily 8 h average (MDA8) O₃ concentrations in China (He et al 2017, Zhao et al 2018, Li et al 2019). Atmospheric circulation is also known to play an important role in the formation and dissipation of O₃ pollution (Zhu and Liang 2013).

Air stagnating (AS) is an index for poor ventilation and stable atmospheric conditions. It favors O₃ precursor accumulation and O₃ pollutant creation on a large scale (Schnell and Prather 2017, Zhang et al 2017, Lin et al 2019). It has been reported that multiday and large-scale O₃ pollution coincide with AS and heat waves in the US.
Schnell and Prather 2017; however, few studies have quantified the contribution of meteorological extremes to Chinese regional O3 pollution (Pu et al. 2017, Gong and Liao 2019, Lin et al. 2019). There is limited knowledge of the relationships between the changes in multiday O3 pollution and meteorological variables over a region (Zhang et al. 2017, Gong and Liao 2019). Considering changes in synoptic and meteorological conditions is important when trying to mitigate regional O3 pollution events. Recent data should be used to explore the synoptic and meteorological drivers affecting Chinese regional O3 pollution events.

This study investigated the response of regional O3 events to different synoptic and meteorological variables across six Chinese regions (figure 1) by considering the spatial extent of these pollution events. The six regions included the Beijing–Tianjin–Hebei (BTH) super-city complex, the Yangtze River Delta (YRD), the Pearl River Delta (PRD), the Sichuan Basin (SCB), the Guanzhong Plain (GZP), and the West Side of the Strait (WSS). The remainder of this paper is organized as follows. Data sources and methods have been described in section 2. The applicable synoptic and meteorological conditions of regional O3 pollution events are summarized in section 3, along with the key drivers that affect event severity. Finally, study implications are discussed in section 4.

2. Materials and methods

2.1. Study region
In China, severe O3 pollution events have primarily occurred in economically developed regions, especially in large cities with significant populations (Wang et al. 2017). Therefore, this study focused on the six major Chinese urban agglomerations (table 1, figure 1). These included (1) the BTH, with 13 cities and 110 million people; (2) YRD, with 18 cities and 127 million people; (3) PRD, with 14 cities and 80 million people; (4) SCB, with 16 cities and 101 million people; (5) GZP, with 11 cities and 45 million people; and (6) WSS, with 20 cities and 93 million people.

For each region, its population are obtained from the National Bureau of Statistics (https://data.stats.gov.cn/index.htm), representing the population in 2019. Boundaries of each city in the six regions were obtained from the Ministry of Civil Affairs of the People’s Republic of China (MCA; http://202.108.98.30/map).

2.2. Data
Observation data on MDA8 O3 concentration since May 2014 were obtained from the China National Environmental Monitoring Center (CNEMC) network; data from March 2015 to February 2019 were used for this study. Moreover, data on the commonly used local meteorological variables that affected O3 concentrations, including the daily maximum air temperature at 2 m \( T_{\text{max}} \), daily mean air temperature at 2 m \( T_{\text{mean}} \), daily
sunshine duration (SD), daily surface air pressure (AP), daily precipitation (Pre), daily relative humidity (RH), and daily 10 m surface wind speed (WS) were acquired from the China National Meteorological Information Center (CNMIC, https://data.cma.cn/).

Other reanalysis meteorological variables, including data for daily sea level pressure (SLP), daily 10 m zonal wind (U10M), daily 10 m meridional wind (V10M), and daily planetary boundary layer height (PBLH) were collected from the NASA Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) data portal (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). Tropical cyclone data for western Pacific were obtained from the Typhoon Network of the China Meteorological Observatory (http://typhoon.nmc.cn/web.html).

### Table 1. The number of cities and the overall population in each region.

| Region  | Number of cities | Population (million) |
|---------|------------------|----------------------|
| BTH     | 13 (National Development and Reform Commission 2015) | 110 |
| YRD     | 18 (National Development and Reform Commission 2016b) | 127 |
| PRD     | 14 (Guangdong Province Development and Reform Commission 2014) | 80 |
| SCB     | 16 (National Development and Reform Commission 2016a) | 101 |
| GZP     | 11 (National Development and Reform Commission 2018) | 45 |
| WSS     | 20 (People’s Government of Fujian Province 2010) | 93 |

### Table 2. Definition of regional O₃ pollution events related metrics.

| Metric                              | Definition                                                                 |
|-------------------------------------|---------------------------------------------------------------------------|
| O₃ pollution event                  | the condition when MDA8 O₃ concentrations ≥160 μg m⁻³                        |
| O₃ pollution day                     | the days with MDA8 O₃ concentrations ≥160 μg m⁻³                           |
| central extreme day                 | the day with the largest number of cities that have O₃ pollution during each regional O₃ pollution event |
| regional O₃ pollution event         | ≥25% cities with O₃ pollution (i.e., MDA8 O₃ concentrations ≥160 μg m⁻³) every day and ≥50% cities with O₃ pollution during central extreme day in each region |
| regional O₃ pollution event intensity (REI) | product of the number of O₃ polluted cities (i.e., MDA8 O₃ concentrations ≥160 μg m⁻³) and their mean MDA8 O₃ concentrations during each O₃ pollution event |

2.3. Defining regional ozone pollution events

The definition of a regional O₃ pollution event is summarized in Table 2. For this study, 160 μg m⁻³ represents the O₃ pollution threshold, based on the Chinese O₃ Grade II air quality standard for an ambient air functional area (Ministry of Environmental Protection of the People’s Republic of China 2012). Regional O₃ pollution event was defined as MDA8 O₃ concentrations ≥160 μg m⁻³ in over 25% of the cities within a region and MDA8 O₃ concentrations ≥160 μg m⁻³ in over 50% of the cities during a central extreme day (People’s Government of Guangdong Province 2013). The central extreme day was defined as the day with the most O₃-polluted cities during an O₃ pollution event (People’s Government of Guangdong Province 2014). MDA8 O₃ event concentration was defined as the mean MDA8 O₃ concentrations for cities that had O₃ ≥ 160 μg m⁻³ during the event. The term ‘regional O₃ pollution event intensity’ was used to quantify the severity of regional O₃ pollution events; it was the product of MDA8 O₃ concentration and the number of O₃ polluted cities during the event (Table 2).

2.4. Statistical analysis

A subjective classification method (Huth et al. 2008) was used to analyze SLP synoptics. Thus, synoptic pressure patterns that were applicable during regional events were identified using daily SLP isobaric charts. To simplify the classification and to reduce bias caused by subjective interpretations, only two common synoptic patterns (high-pressure and low-pressure systems) were used. The summer MDA8 and SLP were detrended by subtracting the 15 d moving averages (from pre- to post-7 days of the date), which helped establish the correlation between the detrended grid SLP and summer MDA8 for each region.

Meteorological variable changes were calculated for all the cities in each region. For each event, it was calculated from the day before to the first day and from the last day to the next day. The variables included Tₓmax, SD, SLP, Pre, daily specific humidity (SH), U10M, and V10M. Air stagnation (AS) was calculated using PBLH and theoretical boundary layer height (TBLH) (Wang et al. 2018a), such that if PBLH was < TBLH and Pre < 0.1 mm, AS would occur (AS = 1); otherwise, AS would not occur (AS = 0). TBLH was calculated from WS.
Table 3. Candidate variables used in the model selection process.

| Variable     | Definition                                      | Source                  |
|--------------|------------------------------------------------|-------------------------|
| intensity of AS | the intensity of air stagnation (km²)            | CNMIC, MERRA-2 and MCA  |
| intensity of HD | the intensity of hot days (km²)                | CNMIC and MCA           |
| SD           | daily sunshine duration (hour)                  | CNMIC                   |
| Pre          | daily precipitation (mm day⁻¹)                 | CNMIC                   |
| SLP          | daily sea level pressure (hPa)                 | MERRA-2                 |
| U10M         | daily 10 m zonal wind (m s⁻¹)                  | MERRA-2                 |
| V10M         | daily 10 m meridional wind (m s⁻¹)             | MERRA-2                 |
| SH           | daily specific humidity (g kg⁻¹)               | CNMIC                   |

\[
TBLH = a \times e^{b \times WS} + c
\]

where, \(a, b,\) and \(c\) were parameters obtained from Wang et al (2018a), which varied seasonally (table S1 (available online at stacks.iop.org/ERC/3/055004/mmedia)). SH was calculated from the \(T_{mean}\) AP, and RH (Song et al 2012).

\[
SH = 6.22 \times \frac{ES \times RH}{AP - 0.378 \times ES}
\]

where, ES indicates the saturated vapor pressure (hPa) and is derived using equation (4):

\[
ES = 6.1078 \times e^{(\frac{35.86 \times T_{mean}}{273.16 + T_{mean}}) - 1.269}
\]

Regional meteorology trends covering > 50% of the cities in any one region were also investigated to explore the dominant meteorology drivers at regional O₃ pollution event onset and completion.

Multiple linear regression (MLR) was combined with the Bayesian information criterion (BIC) method to model the REI for each region, as a function of synoptic and meteorological variables. BIC considers both the goodness of fit and the number of variables in the model. BIC is a technique used to select the combinations of candidate synoptic and meteorological variables that have the best explanatory power (Anderson et al 1998), thus helping identify the predominant meteorological mechanisms associated with REI changes. The BIC model is formulated as follows:

\[
BIC = \sigma \times \ln((y - \hat{y})^2 \div (y - \bar{y}) / o) + n \times \ln(o)
\]

where \(\sigma\) indicates the number of O₃ pollution events in each region, \(\sigma\) denotes the number of selected variables in the MLR, \(\hat{y}\) stands for the estimated REI based on MLR involving a given subset of variables. The variables for the MLR were normalized by subtracting the mean and then dividing by the standard deviation.

All candidate variables used in model selection have been summarized in table 3, including AS, SD, SLP, Pre, SH, U10M, V10M, and hot days (HD), where \(T_{mean} \geq 35 \degree C\) (Tan et al 2010, Meteorological Administration 2017). AS intensity is defined as the sum of the area of O₃ polluted cities with AS during a regional O₃ pollution event, whereas HD intensity is defined as the sum of the area of O₃ polluted cities with HD during a regional O₃ pollution event.

In addition to HD and AS intensities, other meteorological variables were averaged, temporally (i.e., for every day of an ozone event) and spatially (i.e., over all the cities in a given region), during a given O₃ pollution event. Synoptic and meteorological variables of all regional event were normalized before calculating the MLR coefficients, which enabled a fair comparison of the contribution of dominant variables to regional REIs. We have tested all the meteorology combinations with more variables by BIC with MLR. The BIC values and \(R^2\) of the models with two or one variables are similar to the models with more variables. Thus, to minimize the risk of overfitting while maximizing selected model robustness, only models with up to two variables should be considered.

3. Results

3.1. Identifying regional O₃ pollution events

Among the 222 regional O₃ pollution events recorded for the six study regions during 2015–2018, the BTH experienced the maximum number of events (65), followed by the YRD (58). Approximately 95% of these events occurred during the warmer period (April–September) with sufficient sunlight and high temperature (figure 2). Although only four years of data were available, which were insufficient to conclude a significant trend, the number of O₃ pollution events tended to increase since 2015, with the most pronounced increase being observed
in the SCB and GZP. This finding was consistent with that of Gong and Liao (2019), who reported an increasing O₃ pollution trend in North China from 2014–2017.

Regionally, O₃ pollution events in the six regions generally intensified between 2015 and 2018; longer regional events (>7 d) also became more frequent. In the BTH, 20% of the regional O₃ pollution events lasted between 8 and 18 d and covered 92%–100% of the cities in the region. The five worst BTH events occurred during June–July of 2017–2018 (Table S2). These five events affected all the regions during the central extreme day (table 1), with MDA8 O₃ concentrations >187 µg m⁻³.

In the YRD, 10% of the events lasted 8–13 d and covered 94%–100% of the cities. The five worst O₃ pollution events in the YRD occurred during May–September of 2015–2017. These events covered 83%–94% of the cities during the central extreme day, with MDA8 O₃ concentrations >189 µg m⁻³.

In the GZP, three O₃ pollution events in 2017 lasted for more than a week. In the GZP and PRD, the worst O₃ pollution events occurred in 2017, and lasted 11–26 d; they covered 86%–91% of the cities, with MDA8 O₃ concentrations >187 µg m⁻³ (Table S3).

These results confirmed that long-duration regional O₃ pollution events extended across almost all BTH, GZP, YRD, and PRD cities, and lasted for more than a week (MDA8 concentrations >180 µg m⁻³). However, none of the SCB and WSS events lasted longer than a week. Apart from the YRD, O₃ pollution events in the other five regions peaked in 2017 and 2018.

Fluctuations in the O₃ pollution event in the YRD were associated with extreme precipitation in the summer of 2016 (Herring et al. 2018) and with typhoons in 2018 (Meteorological Administration 2018). In the other five regions, the strong western Pacific subtropical high (WPSH) and extreme regional heat waves associated with dry weather (Meteorological Administration 2017, 2018) may have contributed to 2017–2018 experiencing the worst regional O₃ pollution. Overall, irrespective of regional fluctuations, the worst regional events occurred in more recent years (i.e., 2017 and 2018), suggesting an overall acceleration in extreme O₃ pollution patterns over time (Table S3).

The six regional REIs differed in both magnitude and temporal distribution. As shown in figure 2, regional REIs in north China were higher than those in the south. Among the six regions, the WSS REI was only 7% of that in the BTH region across the study period.

Monthly BTH and GZP REIs peaked in June (figures 2a, e), when increasing temperature, stronger solar radiation, and low humidity facilitated higher photochemistry activity levels (Hou et al. 2014, Fang et al. 2020). In contrast, monthly PRD REIs mostly peaked during August–October, and their worst annual O₃ pollution events occurred in September and October (figure 2c). Moreover, monthly O₃ pollution event REIs in south China
often peaked twice, that is in spring and fall, while experiencing a drop in summer. Although high temperatures in summer can intensify O₃ pollution, high precipitation and clear air brought by the East Asian summer monsoon can effectively inhibit extreme regional O₃ pollution in these regions (Li et al. 2018a, Han et al. 2020). Consequently, REIs in south China often decreased during the monsoon, while exhibiting peaks during pre-monsoon and/or post-monsoon.

3.2. Synoptic and meteorological conditions for O₃ pollution events

The changes in T_max affected the onset and completion of most regional O₃ pollution events in the six regions (figure 3). Most O₃ pollution events occurred with increasing T_max meaning that T_max was higher during the first day of an event than the day before the event, whereas most pollution events ended with decreasing T_max meaning that T_max decreased from the last day to the next day of these events. Figure 3(a) demonstrates that 86% of events occurred in regions that were warm, with the highest frequency (96%) occurring in the GZP. Large-scale increases in T_max can lead to the release of more anthropogenic volatile organic compounds (VOCs) and can also change air circulation patterns (Ordonez et al. 2005, Pu et al. 2017). This results in an increase in photochemical processes, which causes regional O₃ pollution. Additionally, 69% of the events in the YRD and GZP started with regional warming and increasing SD trends (figure 3(b)).

Owing to its direct and positive impact on the photochemical processes responsible for O₃ production, SD is also an important variable that influences the occurrence of regional events. Furthermore, 83% of the events in the study area ended with a regional cooling trend (figure 3(c)). Using the SCB as an example, 87% of the events concluded with regional cooling and decreasing SD trends (figure 3(d)). Overall, the start and finish of 69% of the O₃ pollution events in the study area coincided with regional increases and decreases, respectively, in T_max.

Regional O₃ pollution events were strongly influenced by high-pressure systems from the ocean and by cyclones. As oceanic high-pressure systems affected 60% of the BTH, GZP, and YRD events, they were the dominant synoptic systems. Additionally, positive correlations between detrended SLP and summer MDA8 occurred in the Pacific (figure 4), which suggested that the pollution events were dependent on WPSHs.

Continuous WPSHs affected atmospheric circulation, water vapor levels, and O₃ transport (Ding et al. 2013), leading to O₃ accumulation and regional O₃ pollution events (Wang et al. 2018b, Dong et al. 2020). Low-pressure systems in Northeast China also influenced O₃ pollution in the BTH region (figure 4(a)) and affect 45% of the events. The downward airflows at the peripheries of Northeast cold vortexes favored regional O₃ collection and stagnation, giving rise to pollution events.

On the other hand, tropical cyclones were the dominant synoptic systems for pollution events in South China, with 60% of pollution events in PRD and WSS being association with typhoons (cyclones). In South China, negative correlations in the western Pacific showed that tropical cyclones were closely associated with O₃ pollution (figures 4(b)–(c) and (f)). This phenomenon occurred due to the combined effects of high
temperature, strong solar radiation, and large-scale downdrafts at their peripheries (Ding et al 2004, Wang et al 2017, Lin et al 2019). Tropical cyclones stimulated regional O₃ pollution for a short period of time.

Additionally, 65% of the SCB events occurred when there were low-pressure systems in the Qinghai–Tibet Plateau. Positive correlations in southwest China (figure 4(d)) indicated that Tibetan Plateau heat lows were able to influence regional O₃ pollution. The hot dry days caused by weak east heat lows also reportedly exacerbate regional O₃ pollution (Wang and Li 2015).

It was concluded that WPSHs and tropical cyclones with weak hot air circulation represented synoptic patterns that were typically present for most of the O₃ pollution events analyzed in the study area.

To further explore the synoptic and meteorological characteristics of regional O₃ pollution events, co-occurrence frequencies for O₃ pollution days for all the events with candidate variables were examined. Figure 5 shows that AS was a common meteorological condition, often co-occurring (> 50%) in most of the six regions (92% of the cities). Its highest frequency (100%) was found in 50% of the WSS cities (figure 5(a)). Given that AS inhibits horizontal and vertical mixing in the lower troposphere, it leads to the quick generation and collection of O₃ pollutants at the regional level (Cheung and Wang 2001, Garrido-Perez et al 2018). As for HD, lower co-occurrence frequencies (< 50%) accounted for 98% of the six regions (figure 5(b)), although 87% of long-duration events had both AS and HD.

Concurrent with stagnant air and dry hot days, meteorology extremes were crucial synoptic features in the regional O₃ pollution events. The co-occurrence frequency of strong SD with low precipitation (i.e., Pre < 0.1 mm) (General Administration of Quality Supervision 2012) and O₃ pollution days was > 50% in most areas of the GZP (figure 5(c)). Given the positive effect of dry air with strong SD on O₃ generation (Rizk 1992, Shu et al 2020), this combination was associated with the occurrence of pollution events.

The co-occurrence frequency for O₃ pollution days and a south wind (SW) V10M was > 70% in the BTH (figure 5(d)). This dominance showed that SW was a key meteorological feature of these events, transporting significant amounts of O₃ from neighboring southern regions into the BTH (Ma et al 2011, Wang et al 2017).

Overall, the results confirmed that AS was the dominant synoptic condition for most events, while SW pollution transport had a non-negligible impact on regional O₃ pollution in North China.

### 3.3. Key synoptic and meteorological drivers of O₃ pollution events

Key synoptic and meteorological variables were identified for the REI of the five regions (table 4). The six pollution events of the WSS region were not analyzed, as the sample size was extremely small for MLR (Harrell 2015). All regression coefficients were statistically significant for the five regions (p < 0.01).

MLR models developed for all five regions explained 75%–95% of the variability in regional O₃ pollution event intensity (table 4). The optimal MLR model in the BTH showed that the contributions from AS and HD
intensity were positive for REI. This result was similar to that of Ma et al. (2019), who confirmed that heat waves with AS enhanced the contribution of temperature to regional extreme O₃ events in the north China Plain. Recent studies have also suggested that HD with AS can effectively increase O₃ generation and accumulation rates by controlling VOC emissions and peroxyacetyl nitrate chemistry (Jacob et al. 1993, Garrido-Perez et al. 2018).

In 2017–2018, high AS and HD intensities were observed during the top seven worst regional O₃ pollution events. However, in the PRD, increasing AS intensity co-occurring with decreasing V10M aggravated regional O₃ pollution event intensity. Owing to the clean air mass carried by the south wind and O₃ transport caused by the north wind (caused by typhoons), positive V10M (i.e., the south wind) was established to reduce O₃, whereas negative V10M (i.e., the north wind) could make O₃ conditions worse (Wang et al. 2001). This result supported the hypothesis that high AS intensity in the presence of weak north winds caused by tropical cyclones could lead to extreme regional O₃ pollution events.

In the YRD, SCB, and GZP regions, AS intensity was the only dominant regional O₃ pollution event intensity driver. For the YRD, AS strengthened by either WPSH or cyclones raised temperatures and triggered strong photochemical reactions, which lead to extreme regional O₃ pollution events (Gao et al. 2020). For the SCB and the GZP, when large-scale AS phenomena controlled the mountain–basin areas on warm and sunny days, intense O₃-related physical and chemical reactions quickly generated extreme regional O₃ pollution (Li et al. 2018b, Ning et al. 2020). For each region, the regression coefficient for AS intensity was higher than that for other variables, meaning that AS intensity was the dominant driver influencing temporal REI variability.

Overall, the results indicated that meteorological extremes made vital contributions to regional O₃ pollution event intensity variation across the study area.
4. Conclusion and discussion

This study examined O₃ pollution events in the six economically developed regions of China occurred during 2015–2018 and identified their key drivers. O₃ pollution events were the most common during this period. Moreover, AS, under the influence of WPSH or tropical cyclones was associated with regional O₃ pollution events in the study area, with AS intensity being the dominant REI driver in most regions. Additionally, the rise and fall of T_max induced the beginning and end of an O₃ event in most regions.

In China, increasing meteorological extremes, such as the AS (Huang et al 2017) and heat waves (WMO 2019, Wang et al 2019) created suitable meteorological conditions for generating regional O₃ pollution. The short time span of available O₃ monitoring data represented a limitation on the results presented in this study. A longer O₃ observation time series could provide more definitive results, allowing the analysis of synoptic and meteorological drivers, as well as their impacts on the interannual variability in surface O₃ in China, to be presented in a more robust manner.

Global warming and urban expansion could lead more frequent meteorology extremes. In that case, there will be more frequent O₃ pollution in the future (Zhang et al 2018). Thus, mitigating O₃ pollution in China and other countries will involve controlling O₃ precursor emissions. Comprehensive air quality management plans should be implemented by considering weather conditions and emissions to control intense and large-scale O₃ pollution. For example, mandating greater use of public transport during hot days that coincide with air stagnation would be beneficial.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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