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# Assessment of aerosol effective radiative forcing and surface air temperature response over eastern China in CMIP5 models

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**ABSTRACT**

The effective radiative forcing (ERF) and associated surface air temperature change over eastern China are estimated using multi-model results from CMIP5 (Coupled Model Intercomparison Project Phase 5). The model results show that, relative to 1850, the multi-model and annual mean aerosol ERF for the year 2005 is $-4.14$ W m$^{-2}$ at the top of the atmosphere over eastern China (20°–45°N, 105°–122.5°E). As a result of this ERF, the multi-model and annual mean surface air temperature change in eastern China during 1850–2005 is $-1.05$ °C, leading to a climate sensitivity of 0.24 °C/(W m$^{-2}$) in this region.

**摘要**

气溶胶有效辐射强迫是评估气溶胶气候效应的有效指标。本文利用国际耦合模式比较计划（CMIP5）中7个模式的模拟结果，评估了模式对东亚地区气溶胶光学厚度和有效辐射强迫的模拟水平，并分析了东亚地区平均地表温度对局地人为气溶胶强迫的响应。研究结果显示，大部分模式低估了中国东部和西南部污染地区的气溶胶光学厚度，这可能与模式中气溶胶局地排放、化学过程以及模式分辨率有关；多模式平均的东亚地区气溶胶有效辐射强迫为−4.14 W m$^{-2}$，气溶胶在东亚地区有明显的降温效应，1850–2005年气溶胶浓度增加使得东亚地区降温−1.05°C。

## 1. Introduction

Atmospheric aerosols are major air pollutants and have significant impacts on climate change. Aerosols can alter the Earth's radiative balance directly by scattering and absorbing solar radiation, and indirectly by changing cloud properties. The global effective radiative forcing due to aerosol–radiation interaction and aerosol–cloud interaction is estimated to be $-0.45$ ($-0.95$ to $+0.05$) W m$^{-2}$ and $-0.45$ ($-1.2$ to 0.0) W m$^{-2}$, respectively, with very large uncertainties (Myhre et al. 2013).

Radiative forcing (RF) is a useful metric for evaluating the contribution of a specific atmospheric component to climate change. The traditional concept of RF is termed instantaneous RF, defined as the change in net radiative flux at the top of the atmosphere (TOA) or tropopause by the forcing agent (Ramaswamy et al. 2001). For aerosols, the instantaneous RF was mostly estimated for direct and cloud albedo effects in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Forster et al. 2007). Several studies have estimated

the instantaneous aerosol direct RF over East Asia and reported a regional and annual mean forcing of $-2$ W m$^{-2}$ to $-4$ W m$^{-2}$ at the TOA (Chang and Liao 2009; Chung et al. 2010; Gao et al. 2014; Li et al. 2014). Using general circulation models, Chang and Liao (2009) estimated a mean present-day aerosol instantaneous direct RF of $-2.4$ W m$^{-2}$ at the TOA over eastern China (18°–45°N, 95°–125°E), and Li et al. (2014) reported a similar value of $-2.9$ W m$^{-2}$ in East Asia (20°–45°N, 100°–145°E). Based on a regional climate model, Gao et al. (2014) reported the annual mean TOA anthropogenic instantaneous direct RF to be $-3.7$ W m$^{-2}$ over East Asia (10–50.5°N, 70–150°E). In addition to aerosol direct RF, the climate effects of aerosols, such as the cloud lifetime effect and the semi-direct effect, cannot be estimated easily because of the response of climate to forcing. The fifth assessment report of the IPCC provided a new measure of the RF, termed the effective radiative forcing (ERF). Conceptually, ERF is defined as the change in radiation balance at the TOA with ocean conditions held fixed but all other processes allowed to respond to the

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change in aerosols (Myhre et al. 2013). ERF includes rapid adjustments in the troposphere, such as the cloud lifetime effect, the semi-direct effect, and aerosol microphysical effects in mixed-phase, ice, and convective clouds. More recently, some studies have examined the ERF of major anthropogenic aerosols (Zelinka et al. 2014; Forster et al. 2016; Zhang et al. 2016; Wang, Wang, and Zhang 2017). By using the updated aerosol–climate online model BCC_AGCM2.0.1_CUACE/Aero, Zhang et al. (2016) reported that the global mean ERF values of sulfate, black carbon, and organic carbon from 1850 to 2010 were −2.37 W m$^{-2}$, 0.12 W m$^{-2}$, and −0.31 W m$^{-2}$, respectively. Forster et al. (2016) examined the different methods of computing ERF by using two global climate models (HadGEM2 and CESM1), and found that ERF computed with fixed sea surface temperatures has much more certainty than regression based methods. Although previous studies suggest ERF is a better indicator in predicting the climate response to forcing factors, especially for short-lifetime components like aerosols (Lohmann et al. 2010), few studies have reported aerosol ERF over eastern China, where concentrations of aerosols are among the highest in the world.

The surface temperature responses to anthropogenic aerosol forcing over East Asia have been investigated previously via regional and global climate models (Liao, Chang, and Yang 2015). To reduce the uncertainties associated with a single model, a number of studies have used the multi-model results from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor, Stouffer, and Meehl 2012) to examine regional climate change by aerosols in East Asia (Salzmann, Weser, and Cherian 2014; Song, Zhou, and Qian 2014; Li, Zhao, and Ying 2015; Wang, Xie, and Liu 2015; Xu et al. 2015; Zhao, Li, and Zuo 2016). Song, Zhou, and Qian (2014) used 17 CMIP5 models to examine the responses of the East Asian summer monsoon (EASM) to natural and anthropogenic forcing. Their results showed that the cooling over East Asia by anthropogenic aerosols could reduce the land–sea surface temperature contrast and lead to the weakening of low-level monsoon circulation. Similar climate responses of the EASM to anthropogenic aerosols were also reported by Wang,

Xie, and Liu (2015). Based on observations and historical simulations from CMIP5, Zhao, Li, and Zuo (2016) quantified the contributions of anthropogenic aerosols to temperature and precipitation changes in China over the past 50 years. Although significant progress has been made in understanding the aerosol impacts on climate change over East Asia, few previous studies have assessed aerosol ERF in eastern China. Therefore, the objective of this study is to examine the spatial distribution and magnitude of aerosol ERF and the associated surface air temperature response over eastern China by using multi-model results from CMIP5.

## 2. Data and methods

Model results from seven CMIP5 models that participated in simulations of the climatic effects of aerosols for 1850 and 2005 are used (Table 1). The aerosol species are also listed for each model in Table 1. For the purpose of this work, the following CMIP5 simulations are examined:

(1) Two 30-year equilibrium climate experiments ('sstClim' and 'sstClimAerosol'), simulated with prescribed sea surface temperature and sea ice, are used to calculate aerosol ERF, following the IPCC definition of ERF. In the control simulation (sstClim), anthropogenic aerosols are set to preindustrial (1850) levels. The perturbation experiment (sstClimAerosol) is the same as sstClim, except that emissions of anthropogenic aerosols are set to present-day (2000) levels. The aerosol ERF is calculated as the difference in net TOA radiative flux between the perturbed and control runs.

(2) The transient climate experiment ('historicalMisc'), carried out with coupled atmosphere–ocean global climate models for the period 1850–2005. In this experiment, only anthropogenic aerosols are allowed to change with time; other climate forcing agents, such as well-mixed greenhouse gases, ozone, and volcanic

**Table 1.** CMIP5 models used in this study and aerosol species considered in each model. The aerosol indirect effect is considered in all models. The annual mean AOD (aerosol optical depth), aerosol ERF (effective radiative forcing) at the TOA, and the associated change in surface air temperature (ΔT) averaged over eastern China (20–45°N, 105–122.5°E), are also shown.

| Model | Aerosol | AOD | ERF | ΔT |
|---|---|---|---|---|
| CESM1(CAM5) | SO$_4$, BC, OA, DS, SS | 0.20 | −56.17 | −1.14 |
| CSIRO Mk3.6.0 | SO$_4$, BC, OA, DS, SS | 0.61 | −3.32 | −1.24 |
| GFDL CM3 | SO$_4$, BC, OA, DS, SS | 0.45 | −6.67 | −1.47 |
| GISS-E2-R | SO$_4$, NO$_3$, OA, BC, DS, SS | 0.58 | −2.79 | −0.67 |
| IPSL-CM5A-LR | SO$_4$, BC, OA, DS, SS | 0.25 | −2.23 | −0.96 |
| NorESM1-M | SO$_4$, BC, OA, DS, SS | 0.34 | −4.77 | −0.95 |
| CanESM2 | SO$_4$, BC, OA, DS, SS | | −3.04 | −0.90 |
| Mean | | 0.41 ± 0.16 | −4.15 ± 1.61 | −1.05 ± 0.24 |

Notes: SO$_4$, sulfate; NO$_3$, nitrate; OA, organic carbon (including primary organic carbon and secondary organic carbon); BC, black carbon; DS, dust; SS, sea salt.

eruptions, are kept at pre-industrial levels. The differences in surface air temperature between 1850 and 2005 are attributed to the increases of anthropogenic aerosols.

## 3. Results

### 3.1. Simulated aerosol optical depth (AOD)

Among the seven selected CMIP5 models, AOD values are not available from CanESM2. Figure 1 shows the distributions of annual mean AOD at 550 nm from the remaining six models, as well as the multi-model mean, for the year 2005. Also shown in Figure 1 are AOD values at 550 nm from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite retrievals, which have been averaged over 2003–2007 to represent the climatological conditions for 2005. All the models reproduce the high AOD values in eastern China, but show some biases with respect to the exact locations of maximum AOD. For example, the MODIS retrievals show the highest AOD values over North China, the Sichuan Basin, the Yangtze River Delta, and the Pearl River Delta, but most of the models simulate maximum AOD over the Sichuan Basin. The annual mean AOD values averaged over eastern China (20°–45°N, 105°–122.5°E) are shown in Table 1. Relative to the MODIS AOD value of 0.43 (Table 1), CESM1(CAM5), IPSL-CM5A-LR, and NorESM1-M underestimate AOD values by 53%, 42%, and 21%, respectively, while CSIRO Mk3.6.0, GISS-E2-R, and GFDL CM3 overestimate AOD values by 42%, 35%, and 5%, respectively. Over East Asia, the multi-model mean AOD is 0.41, which is very close to the observed mean AOD according to MODIS. Previous studies have suggested that factors such as local anthropogenic emissions, chemistry schemes in different

models and model resolution all contribute to uncertainties of AOD in climate models (Chang et al. 2015).

### 3.2. Aerosol ERF

Figure 2 shows the year 2005 mean aerosol ERF at the TOA from the seven CMIP5 models as well as the multi-model mean values. Aerosol ERF exhibits large negative forcing values in eastern China and along the southeast coast of China. It should be noted that the spatial distributions of aerosol ERF are different from those of instantaneous aerosol direct RF. The spatial patterns of instantaneous aerosol direct RF generally follow those of AOD, with the strongest negative RF values appearing over eastern China and the Sichuan Basin (Han et al. 2011; Chang et al. 2015; Li and Han 2016). Such different spatial distributions between aerosol ERF and the instantaneous direct RF can be attributed to the interactions between aerosols and clouds. Gao et al. (2014) and Shindell et al. (2013) suggested that anthropogenic aerosols have an enhanced effect on clouds in coastal areas, where there are few natural cloud condensation nuclei and high humidity.

Averaged over eastern China (Table 1), the multi-model mean aerosol ERF is −4.14 W m$^{-2}$, which is higher than the TOA instantaneous aerosol direct RF of −2.4 W m$^{-2}$ over eastern China (18°–45°N, 95°–125°E) estimated by Chang and Liao (2009), and that of −2.9 W m$^{-2}$ in East Asia (20°–45°N, 100°–145°E) estimated by Li et al. (2014). This can partly be explained by the inclusion of the aerosol indirect effect in the calculation of aerosol ERF. In addition to the aerosol indirect effect, some of the rapid adjustments induced by aerosol radiative effects in the models also contribute to the difference between ERF and instantaneous RF. These rapid adjustments affect cloud cover or other
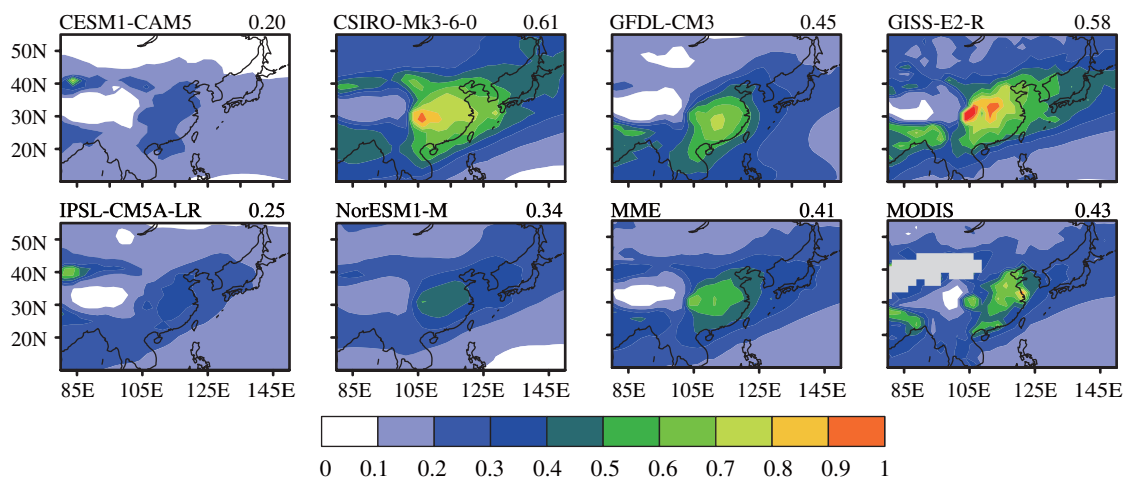


**Figure 1.** Distribution of annual mean AOD at 550 nm according to each CMIP5 model and the multi-model mean for the year 2005. Also shown is AOD at 550 nm from MODIS, which has been averaged over 2003–2007.
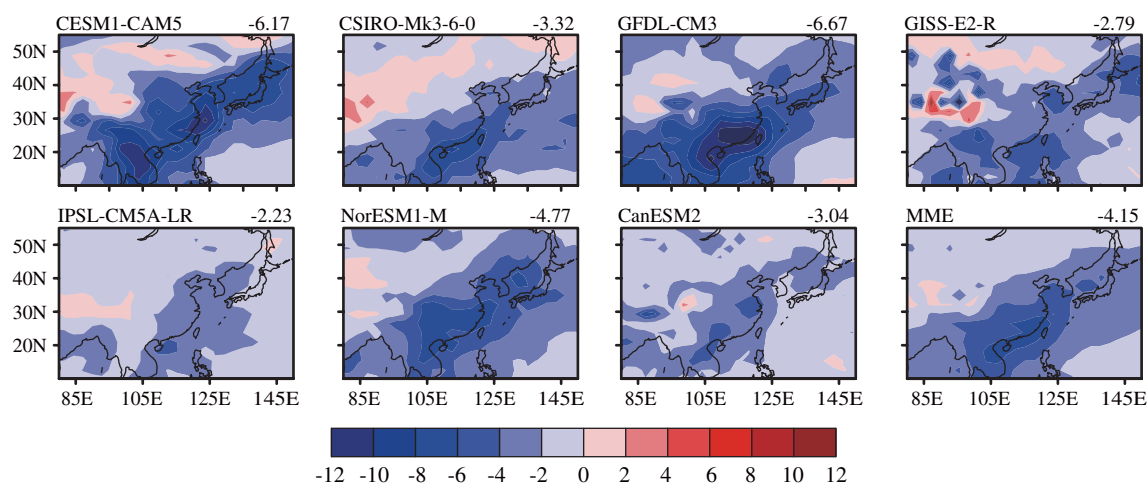
**Figure 2.** Distribution of annual mean aerosol ERF (effective radiative forcing; units: W m$^{-2}$) at the TOA according to the CMIP5 models and the multi-model mean for the year 2005 relative to 1850.

components of the climate system and thereby alter the global budget indirectly (Myhre et al. 2013). For aerosols, such rapid adjustments are particularly pronounced for absorbing aerosols such as black carbon. By modifying the thermal structure of the atmosphere and cloud absorption, absorbing aerosols can alter cloud cover (Hansen et al. 2005; Jacobson 2012). However, it is hard to determine the sign and magnitude of the rapid adjustments, as current models differ in their responses and cannot adequately represent some of the important relevant cloud processes (Boucher et al. 2013). Aerosol ERF varies greatly among the models (Table 1). In addition to the differences in simulated AOD, the uncertainties in ERF also result from the complex interactions between aerosols and clouds. Although the aerosol indirect effect is considered in all the models, the parameterizations of aerosol–cloud interactions are quite different. In GFDL CM3, CAM5.1, and NorESM1-M, the cloud droplet number concentration (CDNC) is dependent on the aerosol composition, size, and number concentration, as well as water vapor saturation. In the other models, CDNC is determined diagnostically via empirical relations between aerosol concentration and CDNC (Ekman 2014).

Positive ERF values are found in some regions in most models, including the Himalayan region and part of northwestern China. This is likely because the surface albedo is very high in those regions, which enhances the effect of absorbing aerosols (Schulz et al. 2006). The positive ERF values can also be attributed to the changes in clouds and longwave radiation induced by the quick adjustment of the atmosphere (Wang, Zhang, and Lu 2014).

### 3.3. Aerosol-induced change in surface air temperature

Figure 3 shows the spatial distributions of changes in surface air temperature (ΔT) over 1850–2005 by aerosol forcing

from the CMIP5 models and the multi-model mean. Most of the models simulate relatively strong cooling in eastern China. However, the location of the largest surface cooling does not follow that of aerosol ERF. For example, most of the models have the largest negative aerosol forcing values over the southeast coast of China, but the largest surface cooling values are found in northeastern China in GFDL CM3, NorESM1-M, and CanESM2. This is because the local temperature changes can be affected by both the change in local radiative flux and the heat transport through large-scale atmospheric or oceanic circulation (Shindell et al. 2010, 2015). As demonstrated by Wang, Wang, and Zhang (2017), anthropogenic aerosols from non-East Asian sources play important roles in changes of temperature over East Asia. Generally, anthropogenic aerosols induce larger cooling over land than over the ocean because of the slower ocean responses (Mickley et al. 2012). The annual and multi-model mean ΔT averaged over eastern China is −1.05 °C (Table 1). This result is consistent with the value reported by Li, Zhao, and Ying (2015), who reported the aerosol-induced surface cooling rate to be in the range of −0.86 to −0.76 °C/(100 yr) over China from 1901 to 2005.

We calculate the correlation between regionally averaged aerosol ERF and ΔT over eastern China (ERF and ΔT in Table 1) for all the models (Figure 4). There is a strong linear relationship between aerosol ERF and ΔT. The correlation is statistically significant and fairly high ($r = 0.7$; $p < 0.05$). The slope of the linear regression is 0.24 °C/(W m$^{-2}$). This value represents the regional climate response per unit local RF, as defined by Shindell and Faluvegi (2009). The regional climate response over eastern China obtained in this study is consistent with the result reported by Shindell and Faluvegi (2009), who investigated the regional climate response to different types of RF and found the regional climate response over the latitudinal banding of 28°–60°N to be about 0.25 °C/(W m$^{-2}$) for sulfate aerosol.
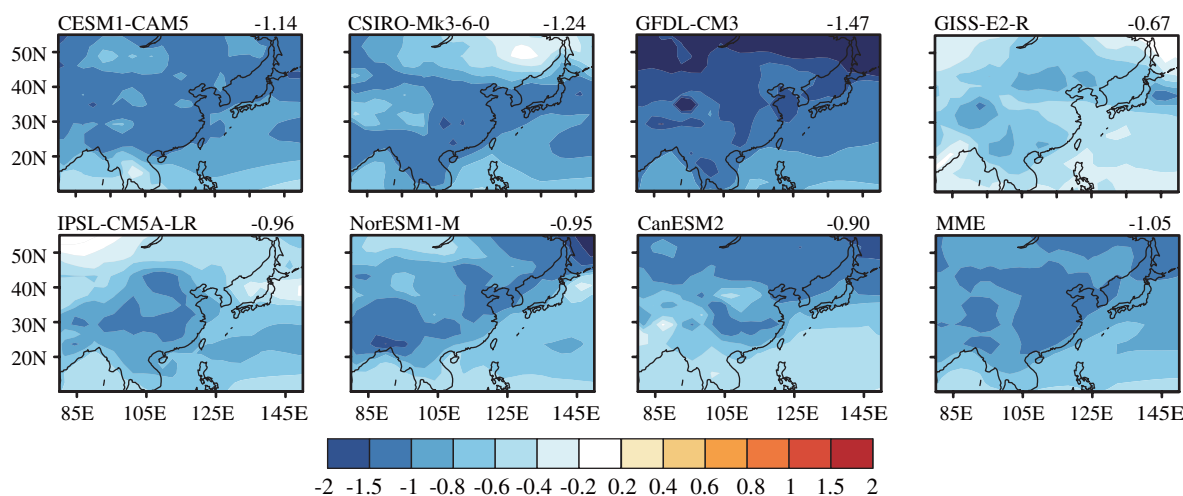
**Figure 3.** Simulated annual mean aerosol-induced changes in surface air temperature (units: °C) according to the CMIP5 models and the multi-model mean for the year 2005 relative to 1850.
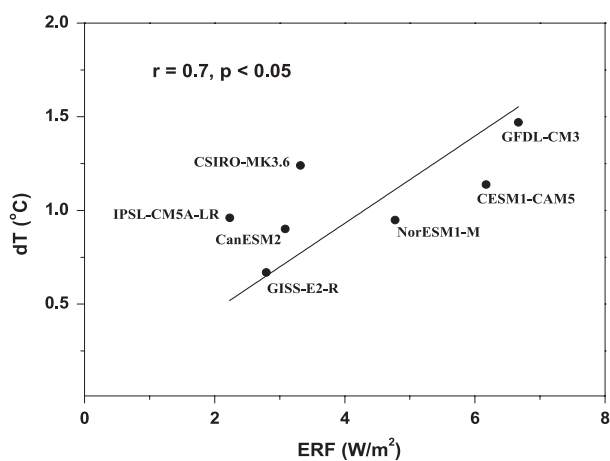


**Figure 4.** Annual mean aerosol-induced surface air temperature change (d*T*; units: °C) versus aerosol effective radiative forcing (ERF; units: W m$^{-2}$) across models.

Notes: The temperature changes and aerosol ERF values are averaged over eastern China (20°–45°N, 105°–122.5°E). Absolute values of d*T* and ERF are used in the plot. The correlation coefficient (*r*) and statistical significance (*p*) are also indicated.

## 4. Summary

In this study we use the results from seven CMIP5 climate models to examine the spatial distribution and magnitude of aerosol ERF and the associated surface air temperature response over eastern China (20°–45°N, 105°–122.5°E) in the period 1850–2005. The results indicate that all the models reproduce high AOD in eastern China. Over eastern China, the multi-model mean AOD is 0.41, which is very close to the observed mean AOD according to MODIS.

Aerosol ERF exhibits large negative forcing values in eastern China and along the southeast coast of China. The spatial pattern of aerosol ERF does not follow that of

AOD. The multi-model and annual mean aerosol ERF is −4.14 W m$^{-2}$ over eastern China, which is higher than the instantaneous direct RF in this region reported in previous studies. Based on the regionally averaged aerosol ERF and surface air temperature change over eastern China for all the models, the regional climate response to aerosol ERF is estimated to be 0.24 °C/(W m$^{-2}$) over eastern China.

It should be noted that our analysis related to ERF and surface air temperature change has uncertainties. Firstly, as shown by previous studies, uncertainties in local anthropogenic emissions, chemistry schemes in different models, and model resolution all contribute to uncertainties in AOD and direct RF in CMIP climate models (Chang et al. 2015). Secondly, uncertainties in aerosol–cloud interactions, owing to the complex microphysical processes involved, lead to uncertainties in estimated ERF and climate responses. Thirdly, in our calculation of the correlation between regionally averaged aerosol ERF and surface air temperature response, we consider only the effect of local aerosol ERF. However, the regional surface temperature response can be influenced by both the changes in local radiative flux and by heat transport through large-scale atmospheric or oceanic circulation (Shindell et al. 2010). All these issues need to be examined further in future studies.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

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