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INVESTIGATION OF DUST SCHEMES IN THE MODEL WRF/CHEM

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ABSTRACT:

Introduction: In this study, the dust schemes implemented in the model WRF/Chem have been investigated for a severe dust storm as a case study over the Middle East.

Materials and methods: There are three main dust schemes in the model WRF/Chem, which are named GOCART, AFWA, and UoC. All of these dust schemes use the same dust source function, based on a topographical method, which plays a crucial role in the simulation of dust emission from the ground.

Results: The results of model for dust distribution are validated by the EUMETSAT MSG dust product, and furthermore the capabilities of the model are investigated by comparing the model output with the measured PM_{10} concentrations of 3 air pollution monitoring stations. The AFWA dust scheme showed better capability in the simulation of dust behavior considering dust distribution. Although the GOCART dust scheme shows a remarkable coincidence between modeled and measured dust concentration, its results are with a considerable overestimation over the study domain. The UOC dust scheme, except Kerman station, shows a drastic underestimation in dust concentration as well as dust distribution.

Conclusions: The results show appropriate estimates of dust distribution and its movement through east. The model WRF/Chem as a state of the art numerical model could be applied in the operational forecast systems for the hazardous

INTRODUCTION

Despite of extensive researches into the cause of dust and sand storms over the recent years, there are a lot of questions about the contributing factors leading to dust emissions and transportations, which have a high degree of uncertainty in identifying dust sources and the processes relevant to dust emission. Investigation and analysis of dust emission include various microscale and mesoscale meteorological processes such as those in the atmospheric mixing layer and air flows over mountains. Microscale processes inside the atmospheric boundary layer are mainly parameterized in the atmospheric models [1] . The amount of dust emission is proportional to the wind energy applied on the erodible soil surface [2]. Dust flux is usually modeled by the parameter of fric-

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tion velocity (u*), which is a criterion for defining turbulent flow near the ground surface [3]. Friction velocity is the square root of the ratio of shear stress to air density. The minimum friction velocity is defined as threshold friction velocity which is an important factor in estimation of dust flux. The motion of soil particles caused by wind, depends on particle size and wind speed. Dust emission models analyze two main transportations of particles. Finest particles with diameters less than 60 µm can be suspended a long time in the atmosphere and be transported thousands of kilometers by the turbulent flows inside the boundary layer. This kind of motion is named the suspension. Particles with diameters between 70 and 500 µm are less affected by turbulent atmospheric flows; hence they follow straighter paths with frequent bounce, called saltation [4]. Saltation is the main process in dust emissions from the surface, while the role of aerodynamic processes in particle emissions are negligible in comparison with saltation [5]. Therefore, some of theoretical models assume that the vertical flux of sand and dust particles is proportional to horizontal flux of saltation. The mathematical equations of sand and dust emissions are discretized and implemented in numerical weather and air quality models; and are validated by running the model for various case studies.

In another research, three dust schemes of implemented on the model WRF/Chem for a severe sand and dust storm occurred on April 2007 was investigated. They concluded that the difference between the calculated vertical fluxes by these dust schemes are proportional to 10^1 for sand particles and 10^2 for clay particles [6]. Convective dust emission occurs when saltation due to turbulent flow is weak. In convective emission, the diameters of soil particles, binding forces between the particles, and surface sheer stress are modeled by stochastic methods [7]. By a combination of analytical and numerical methods [8], a physical approach was developed to parameterize sand and dust emissions which is only dependent on friction velocity and threshold friction velocity. This approach takes into account two processes which are neglected in many parameterizations. The two processes are the increase of soil capability in dust emission due to saltation when the soil erodibility increases, and the increase of dust flux by wind speed, when the soil erodibility decreases. By using physical-based schemes in the model WRF/Chem and a simplified dust scheme [9], dust concentration was estimated and it was determined that the model WRF/Chem has a good performance in the simulation of general meteorological conditions, which is the main cause of the generation of sand and dust storm. They compared the simulated dust concentration and aerosol optical depth (AOD) with the measurement data of AERONET network. Their results showed a good agreement between the spatiotemporal variations of the simulated AOD and dust concentration with those of the observations. Dust source function as a key contributor in estimating the potential flux of sand and dust particles for the west Asia has been improved in a recent research [10]. The new dust source function (WASF) is developed from the analysis of several years of satellite images. By implementing WASF in the default erosion field in the WRF/Chem model, the distribution of dust sources and soil erosion is improved and therefore the model shows more accurate results for dust concentration.

MATERIALS AND METHODS

Dust source function is a coefficient proportional to the erodible soil which has a key role in dust schemes. The current dust source function , Eq.

(1), in the model WRF/Chem is calculated by a topographical approach [11].

$$S = \left(\frac{z_{max} - z_i}{z_{max} - z_{min}}\right)^5 \quad (1)$$

In Eq. (1), S is the probability of sediments to be accumulated in the grid point number i, with an elevation of zi. zmax and zmin are the maximum and minimum elevations around the grid i with an area of 10 × 10 degrees in the geographical scale. The model WRF/Chem is the state of the art numerical air quality model which simulates air quality simultaneously (online) with the meteorological processes. By the advantage of online weather and air quality modeling, it is possible to consider aerosol's indirect effects on weather, such as cloud formation. In the following sector, we provide short descriptions of each three dust schemes implemented in the model WRF/Chem.

GOCART dust scheme

The model GOCART is the main dust scheme implemented in the model WRF/Chem. Two other dust schemes are based on GOCART. The main components of aerosols such as sea salt and black carbon are simulated by the model GOCART. This model for the simulation of dust concentration needs to have 10 m wind speed, threshold friction velocity, soil features, particularly soil erosion. In Eq. (2), for the class p of dust diameter, vertical dust flux is estimated as follows:

$$F_p = CS\, s_p\, u^2 (u - u_t) \ \ if\ u > u_t \quad (2)$$

In Eq. (2), C is a constant equal to 1 mg $s^2 m^{-5}$, s_p is the ratio of each particle in the soil, u and u_t are 10 m wind speed and threshold wind speed. S is soil erosion.

AFWA dust scheme

AFWA dust scheme has been developed be the researchers at the Air Force Weather Agency (AFWA) and Atmospheric and Environmental Research (AER). This dust scheme is based on GOCART dust model. Main aspects of AFWA dust scheme include enhancements to the modeling of saltation process and the distribution of emitted particle size. Furthermore, the impact of soil moisture on the dust lofting threshold has been modified. Dust vertical flux in AFWA dust scheme is estimated by the saltation flux , Eq. (3):

$$H = C\frac{\rho_a}{g} u_*^3 \left(1 + \frac{u_{*t}}{u_*}\right)\left(1 - \frac{u_* t^2}{u_*^2}\right) \quad (3)$$

In Eq. (3), C is an empirical constant, ρ_a is air density, g is the gravity acceleration, and u_* and u^*_t are friction velocity and threshold friction velocity, respectively. Using Eq. (3), vertical dust flux is estimated by the Eq. (4):

$$F_{bulk} = H\alpha * S \quad (4)$$

In Eq. (4), α is the saltation ratio which increases proportional to clay percent of the soil; and S is the dust source function.

UoC dust scheme

UoC (University of Cologne) dust scheme is based on GOCART and is a new approach in estimating dust emissions with regard to particle sizes. Eq. (5) shows the parameterizations used in the UoC dust scheme:

$$F(d_i, d_s) = c_y \eta_f \left[(1-\gamma) + \gamma\sigma_p\right](1 + \sigma_m) g \frac{Q_{ds}}{u_*^2} \quad (5)$$

In Eq. (5), $F(d_i, d_s)$ is dust flux with the size of d_i and saltation flux of d_s, C_y is a dimensionless quantity, η_f is the ratio of emitted dust, σ_m is the saltation coefficient, σ_p is the ratio between the suspended dust particles and the total accumulated particles, γ is the accumulated emission coefficient, Q_{ds} is the saltation flux for the bin size of d_s, and g is the gravity acceleration.

RESULTS AND DISCUSSION

METEOSAT Dust RGB product images have been used in order to identify an appropriate dust episode as our case study. The considered dust episode has occurred on the 1st, 2nd, and 3rd of April, 2015, around the Persian Gulf. In Dust RGB images, areas with magenta color represent dust cloud. Table 1 presents the calculation of the main bands of red, green, and blue of Dust RGB images.

For instance, the red color of Meteosat Dust RGB images is produced by the difference between the reflectance values on the channels 10.8 and 12.0 µm. Other colors are produced by a similar method indicated in Table 1, and a standard RGB image will be generated. These images have been used to verify the spatiotemporal variations of the outputs of the model WRF/Chem for the simulated dust clouds.

The WRF/Chem simulation for dust concentration has been carried out for 3 days and 12 h between Mars 31, 2015 and April 4, 2015. For the initial and boundary conditions, GFS (Global Forecast System) data have been used with spatial resolution of 0.5°×0.5° in geographical system and temporal resolution of 3 hours. WRF/Chem simulation domain, Fig. 1. (a), has been set to cover parts of the Middle East, exposed by the dust episode.

Table 1. Meteosat Dust RGB product

Beam	Channel
Red	IR12.0 – IR10.8
Green	IR10.8 – IR8.7
Blue	IR10.8

Fig. 1 illustrates the WRF / Chem simulation domain (a) as well as soil erosion map (b) of the study area based on the default dust source function implemented in the model WRF/Chem. According to Fig. 1, vast areas of Iraq including Tigris and Euphrates watershed are identified as the main dust sources of the region.

Fig. 2 illustrates dust concentrations, simulated by the model WRF/Chem with three dust schemes. Dust distribution maps have been compared with the Meteosat dust RGB images. Location of the Persian Gulf is determined by white squares in the images of Fig. 2. The comparisons between model output for dust concentration ($PM_{2.5}$ and PM_{10}) and measurements (meteorology stations of Ahvaz, Shiraz, and Kerman) for each of the 3 dust schemes are shown in Fig. 3. The reason for selecting these stations was their data availability and their proximity to the path of the dust storm.

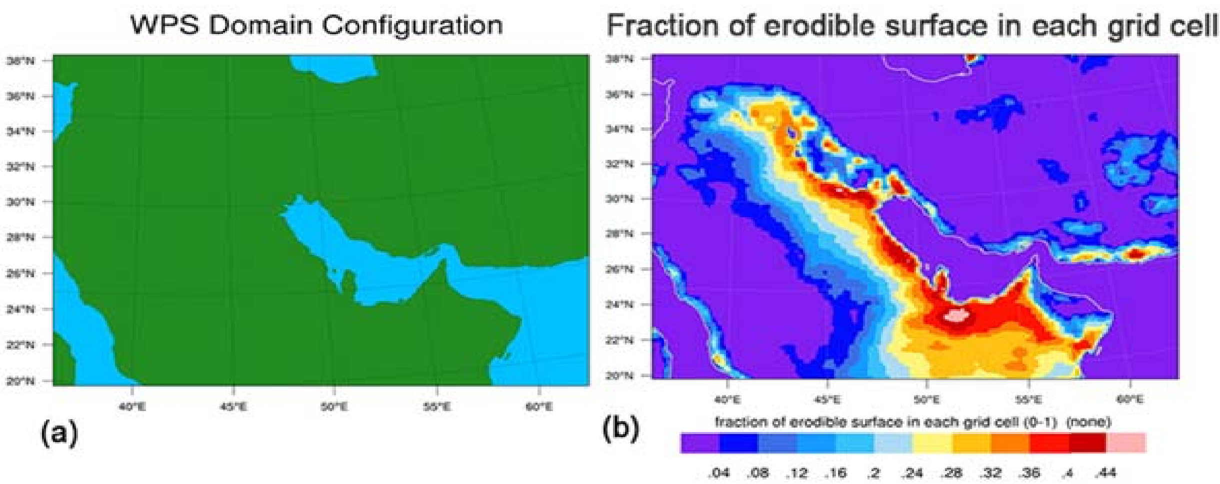

Fig. 1. (a) WRF/Chem simulation domain and (b) soil erosion map

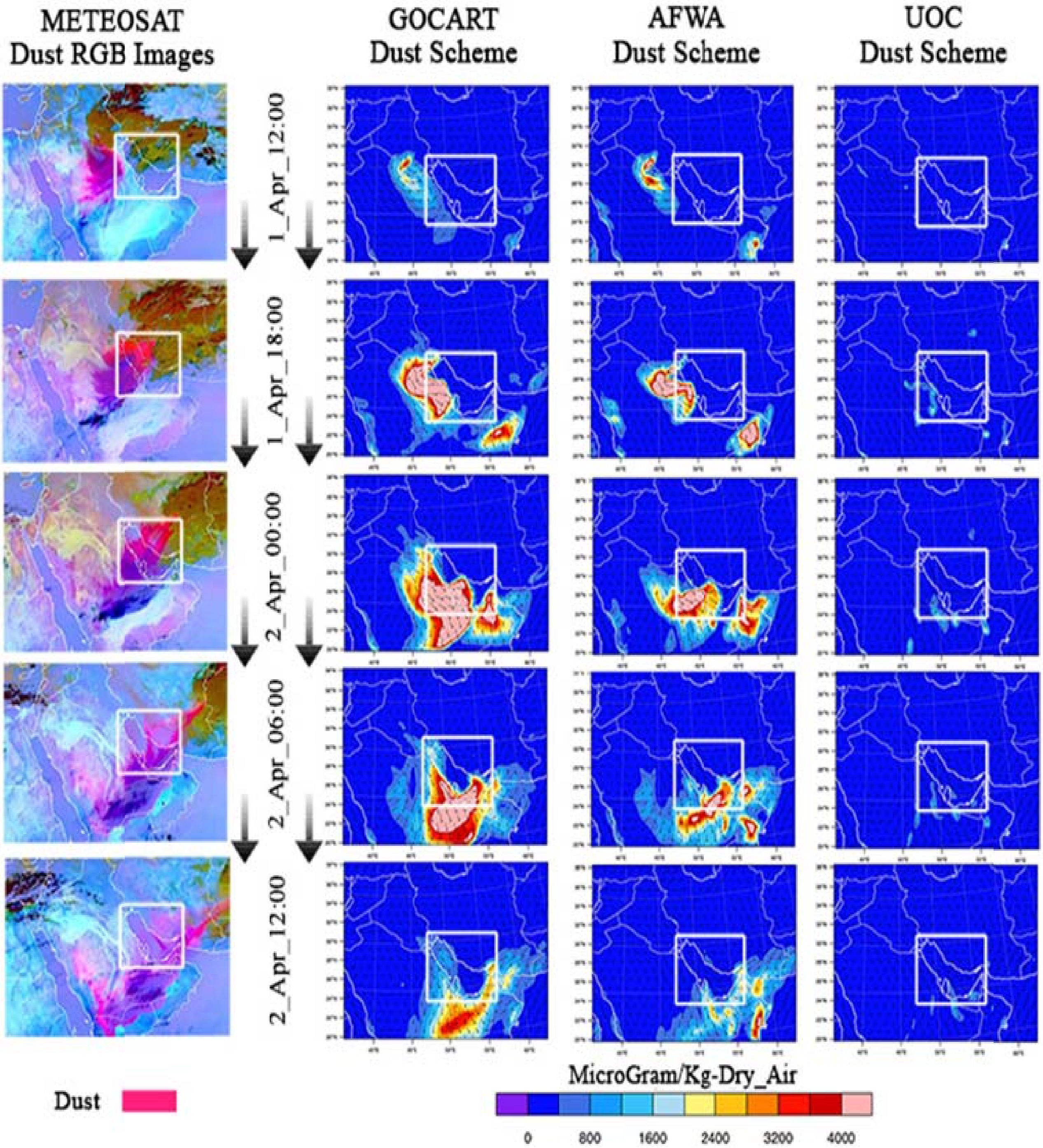

Fig. 2. WRF/Chem outputs of dust concentration from three dust schemes (GOCART, AFWA, and UOC), and the Meteosat Dust RGB images of dust clouds

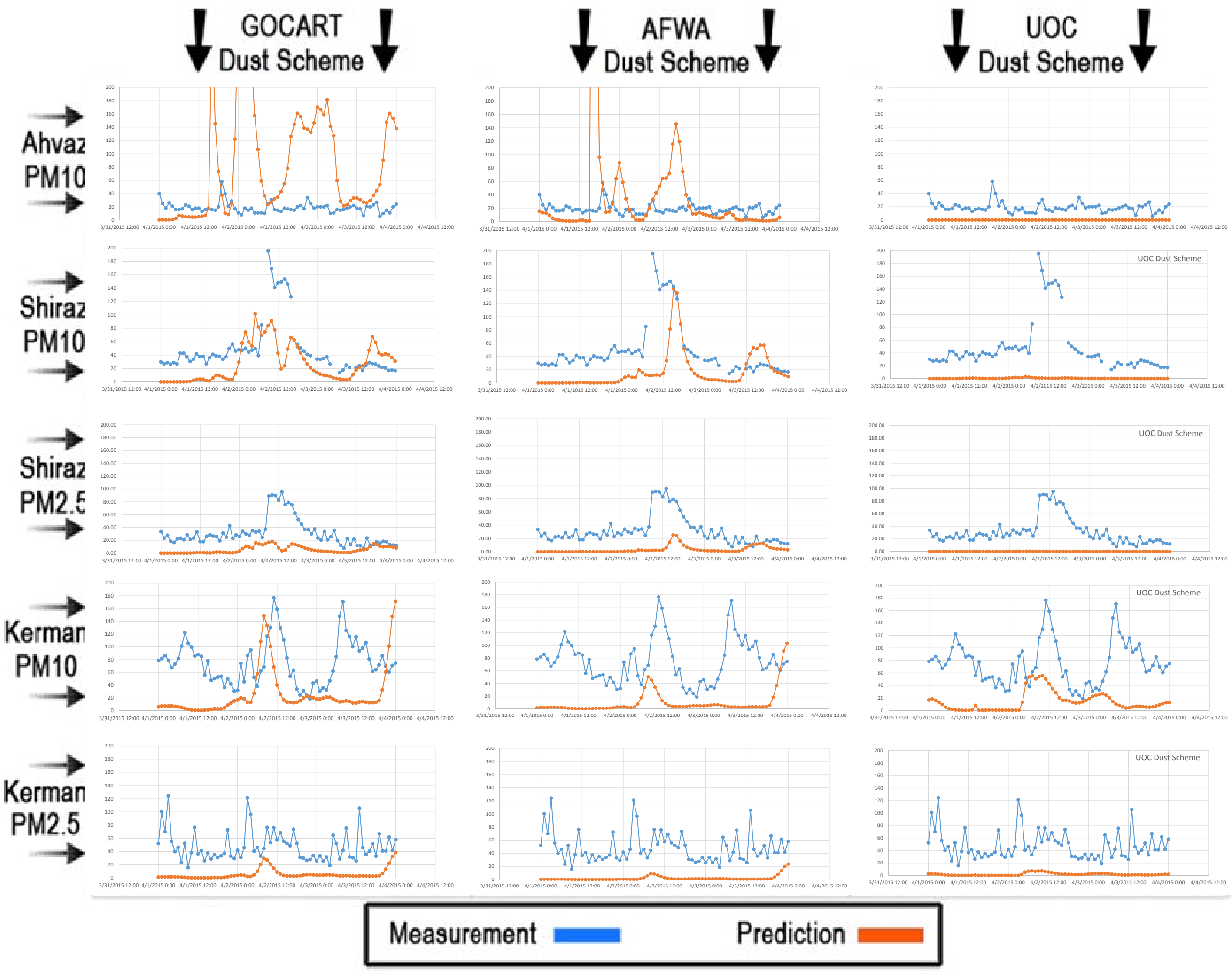

Fig. 3. Comparisons of the time series of the simulated dust concentrations to measurement data (PM_{10} and $PM_{2.5}$)

CONCLUSIONS

According to Fig. 2, the Meteosat Dust RGB images (Magenta color) indicate that dust outbreak appeared in the south west of Persian Gulf and gradually moved towards south east of Iran. Regarding the model outputs for this dust episode, three dust schemes of GOCART, AFWA, and UoC compares fairly well with the Meteosat Dust RGB observation images. The model had a good performance in simulating the transport of dust cloud toward north east of Iran which proves that the model WRF had a realistic simulation of the wind field. The important point is that the Dust RGB images show the columnar mass of dust, whereas the model outputs show the surface dust concentration. One of the main reasons that the modeled dust cloud does not show an accurate agreement with the Meteosat Dust RGB images, is the upper level air flows, which causes the modeled dust cloud of the surface to be different from that of the upper levels.

The general patterns of dust simulations by the three dust schemes are almost similar, which is expected due to the same dust source functions which is used for all of the dust schemes. The AFWA and particularly the UoC dust schemes show considerably lower concentrations that GOCART dust scheme. Regarding Fig. 3, the observational data show better agreement with the model outputs for PM_{10} than $PM_{2.5}$ which is due to the movement of dust storm and the rise of the ratio of PM_{10} to $PM_{2.5}$. According to Fig. 3, maximum values of PM_{10} are 200 µg / m^3. By investigating the observed PM_{10} concentrations, the Ahvaz station has not been affected by the dust storm, while the output of AFWA and GOCART dust schemes has shown considerable overestimation for the Ahvaz station. One of the key contributors to the errors in the model output for dust concentrations is due to the uncertainties in the soil erosion parameter. The UoC dust scheme shows very low values of dust concentrations which could be due to some flaws in the UoC dust module. Generally the GOCART dust scheme has shown the highest over - estimation, although for PM_{10}, Kerman station compares well with the measurement data. The AFWA dust scheme, same as GOCART, over-estimates dust concentration for Ahvaz station, but exhibits a good agreement with the measurement data of Shiraz station. According to Fig. 2, the distribution of dust clouds, is better simulated by the AFWA dust scheme, than the other two dust schemes of GOCART and UoC. Further research is needed to reach a comprehensive assessment of the WRF/Chem dust schemes, particularly for dust episodes in various seasons of the year.

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COMPETING INTERESTS

The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

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ETHICAL CONSIDERATIONS

Authors are aware of, and have complied with, best practices in ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission and manipulation of figures, competing interests, and compliance with policies on research ethics.

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