Estimation of Gridded Atmospheric Oxygen Consumption from 1975 to 2018

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ABSTRACT

Atmospheric Oxygen (O2) is one of the dominating features that allow the earth to be a habitable planet with advanced civilization and diverse biology. However, since the late 1980s, observational data have indicated a steady decline in O2 content on the scale of parts-per-million level. The current scientific consensus is that the decline is caused by the fossil-fuel combustion; however, few works have been done to quantitatively evaluate the response of O2 cycle under the anthropogenic impact, at both the global and regional scales. This paper manages to quantify the land O2 flux and makes the initial step to quantificationally describe the anthropogenic impacts on the global O2 budget. Our estimation reveals that the global O2 consumption has experienced an increase from 33.69 ± 1.11 to 47.63 ± 0.80 Gt (gigaton, 10^9 t) O2 yr⁻¹ between 2000 and 2018, while the land production of O2 (totaling 11.34 ± 13.48 Gt O2 yr⁻¹ averaged over the same period) increased only slightly. In 2018, the combustion of fossil-fuel and industrial activities (38.45 ± 0.61 Gt O2 yr⁻¹) contributed the most to consumption, followed by wildfires (4.97 ± 0.48 Gt O2 yr⁻¹) as well as livestock and human respiration processes (2.48 ± 0.16 and 1.73 ± 0.13 Gt O2 yr⁻¹, respectively). Burning of fossil-fuel that causes large O2 fluxes occurs in East Asia, India, North America, and Europe, while wildfires that cause large fluxes in comparable magnitude are mainly distributed in central Africa.

Key words: oxygen (O2) cycle, climate change, anthropogenic activities

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1. Introduction

The global carbon cycle has responded forcefully under the impact of increasingly intensive human activities, which has already been addressed by voluminous literature on both the global and regional scales in the recent decades (Huang et al., 2007; Luysseert et al., 2007; Li et al., 2012; IPCC, 2014; Chen et al., 2017). Knowledge of this process is not only essential for understanding the history of earth system, but also of critical significance for guiding the future of human beings. In the meantime, as an indispensable component in the global biogeochemical cycle, the oxygen (O2) cycle is also responding substantially to the global change. The O2 and carbon cycles are coupled with each other by a variety of processes including respiration and photosynthesis (Keeling and Manning, 2014). However, they also act separately since there are other processes, including the oceanic outgassing of O2 (mostly due to ocean water warming), photolysis of water, oxidation of minerals, etc., in which carbon doesn’t involve (Petsch, 2014; Royer, 2014). Equivalent in magnitude to the increase in atmospheric CO2, the annual decline in O2 is approximately an average of 4 ppm yr⁻¹. The dependency of humankind and other living organisms on atmospheric O2 cannot be overemphasized since an equable O2 in the atmosphere is pivotal to life (Petsch, 2014). Hence, attention should be paid to the difference between the carbon and O2 cycles and it is necessary to conduct systematic investigations on the O2 cycle independently (Shi et al., 2019), especially under the impact of anthropogenic activities. Obviously, burning of fossil-fuel that causes both the increase in CO2 and decrease in O2 cannot be diagnosed as the only reason explaining the recent O2 decline. Other processes,
including respiration, photosynthesis, burning of organic matters, etc., should also be taken into account (Huang et al., 2018).

Previous studies have assumed that a constant atmospheric O\textsubscript{2} concentration remains under the condition that individual components of the budget are time-independent (Bender et al., 1994a, b). However, ever since the Industrial Revolution, extensive fossil-fuel combustions have emitted a substantial volume of CO\textsubscript{2} into the atmosphere (IPCC, 2014; Zhai et al., 2018), and simultaneously removed substantial amounts of O\textsubscript{2}. This has resulted in changes in both the CO\textsubscript{2} and O\textsubscript{2} cycles on the same order of magnitude as the natural variability. The polar ice core analysis indicates that the decline in atmospheric O\textsubscript{2} is related to burning of fossil-fuel since the beginning of the Industrial Revolution (Battle et al., 1996). Previous research has shown that cumulative emissions from the fossil-fuel and land-use change were 615 ± 80 Gt C, which were portioned among the atmosphere (25 ± 5 Gt C), ocean (150 ± 20 Gt C), and land (190 ± 50 Gt C; Le Quéré et al., 2018). However, it seems that discussions on the individual feedback of each member in the O\textsubscript{2} cycle to human activities are currently lacking. Quantitative estimations of each component and its temporal variation (e.g., O\textsubscript{2} production from terrestrial and oceanic ecosystems, O\textsubscript{2} consumption due to human activities, etc.) in the O\textsubscript{2} cycle are needed to reveal the response of O\textsubscript{2} cycle under the background of human-induced climate changes.

In addition, past studies considered the O\textsubscript{2} budget only at the global scale and roughly presented the global average value of each component. Nevertheless, the consumption and production of O\textsubscript{2} over land are not uniform and may vary with locations due to the intensity of human activities (e.g., economic development, population density, etc.) and natural conditions (vegetation coverage, phenology, etc.). In some areas where massive anthropogenic O\textsubscript{2} fluxes occur, the local O\textsubscript{2} consumption can far exceed its local production; maintaining local O\textsubscript{2} levels then requires O\textsubscript{2} transport from other regions where production exceeds the consumption via atmospheric circulation. Therefore, a global O\textsubscript{2} budget on a grid scale needs to be established to map the spatial characteristics of O\textsubscript{2} budget, which helps to identify the source and sink of atmospheric O\textsubscript{2} in the warming climate. The result is promised to provide a novel viewpoint in assessing the ecological security, sustainable development, habitability for human settlements, etc., from the perspective of atmospheric O\textsubscript{2}.

In this paper, we present a systematic estimation of global O\textsubscript{2} consumption on a resolution of 1.0° × 1.0° over the globe. The product covers four major types of O\textsubscript{2} consumption processes (fossil-fuel combustion, respiration of human and livestock, and wildfires). We also compare our data with the O\textsubscript{2} production from the terrestrial ecosystem and present an O\textsubscript{2} balance over land. At the end of this paper, data uncertainties are estimated by using the Monte Carlo method, and we validate our estimated O\textsubscript{2} fluxes against observations. The O\textsubscript{2} flux data proposed in this paper can be downloaded at https://doi.org/10.1594/PANGAEA.899167 with a resolution of 1.0° × 1.0° ranging from 1975 to 2018 (Liu et al., 2019).

2. Datasets and methods

2.1 Estimation of global O\textsubscript{2} fluxes

In this study, the four O\textsubscript{2} consumption processes listed in Table 1 are considered. The contribution from long timescale processes, such as oxidation and weathering, are negligible compared with the short O\textsubscript{2} cycle timescale considered here (Royer, 2014; Stolper et al., 2016). With regards to the wildfire-induced O\textsubscript{2} flux, some of the wildfires are natural ones, while others are started by humans, e.g., burning of agricultural waste and deforestation. In the quantification of O\textsubscript{2} balance in the terrestrial ecosystem, the wildfire component is included as part of O\textsubscript{2} consumption fluxes and it is excluded from O\textsubscript{2} production fluxes from terrestrial ecosystems (see Section 3.4). An overview of the data sources used to estimate global O\textsubscript{2} fluxes is shown in Table 1.

2.1.1 O\textsubscript{2} fluxes due to consumption by fossil-fuel combustion

The comprehensive information from the Carbon Dioxide Information Analysis Center (CDIAC; Andres et al., 2016), the Open-source Data Inventory for Anthropogenic CO\textsubscript{2} (ODIAC; http://www.odiac.org/), the Emissions Database for Global Atmospheric Research (EDGAR; Janssens-Maenhout et al., 2019), and the PKU (Peking University)-CO\textsubscript{2} (Wang et al., 2013; Liu et al., 2015; http://inventory.pku.edu.cn/) are collected. The EDGAR data estimate the emissions according to the emission sectors specified by the Intergovernmental Panel on Climate Change (IPCC) methodology and distinguish between (1) long-cycle CO\textsubscript{2} emission from fossil-fuel and industrial processes (the “CO2_excl_short-cycle_org_C” data) and (2) short-cycle CO\textsubscript{2} emission, including agriculture burning (the “CO2_short-cycle_org_C”), etc. In this paper, the “CO2_excl_short-cycle_org_C” data of EDGAR are selected since the short-cycle burning processes are considered in other components of our estimation (wildfires). As for CDIAC,
Table 1. Data sources used in this study to estimate the global O\textsubscript{2} flux

| Component          | Sub-component                                      | Data source                                  | Time            | Spatial resolution |
|--------------------|----------------------------------------------------|----------------------------------------------|-----------------|-------------------|
| Fossil-fuel combustion | Solid fuel (coal)                             | CDIAC\textsuperscript{1}                      | 1751–2013       | 1° × 1°           |
|                     | Liquid fuel (oil)                                | EDGARv5.0                                    | 1970–2018       | 0.1° × 0.1°       |
|                     | Gas fuel (natural gas)                           | ODIAC2018                                    | 2000–2017       | 1° × 1°           |
|                     | Flared gas                                        | PKU-CO\textsubscript{2}                      | 1960–2014       | 0.1° × 0.1°       |
| Human respiration   | Male and female                                   | World Population Prospects 2019               | 1990–2020       | National data     |
|                     |                                                   | Global dataset of gridded population and GDP scenarios | 1980–2010       | 0.5° × 0.5°       |
| Livestock respiration | Buffaloes, cattle, chicken, ducks, goats, horses, pigs, and sheep | Gridded livestock data | 2010            | 5° × 5°           |
| Wildfire            | Agricultural waste burning, boreal forest fires, peat land fires, temperate forest fires, tropical forest fires, and savanna fires | Global fire emissions database, version 4.1 (GFED v4) | 1997–2016       | 0.25° × 0.25°     |

\textsuperscript{1} Both the gridded annual emission estimates and national tabular data from CDIAC were used.

ODIAC-2018, and PKU-CO\textsubscript{2}, the data that only cover the emissions from fossil-fuel burning are used in this paper. Therefore, the global total CO\textsubscript{2} emission in EDGAR is slightly higher (about 1.5 Gt CO\textsubscript{2} a\textsuperscript{−1}) than that in the other three datasets, because EDGAR includes the emissions from industrial processes (chemical production, metal production, etc.).

Carbon emissions from the above-mentioned data sources are aggregated and the ensemble mean of carbon emissions is calculated for the conversion from carbon to O\textsubscript{2} fluxes. The O\textsubscript{2} flux due to consumption by fossil-fuel combustion can be converted from the emission of carbon according to the chemical equation below:

\[
C_xH_y + \left(x + \frac{1}{4}y\right)O_2 \rightarrow xCO_2 + \frac{1}{2}yH_2O. \tag{1}
\]

Due to fuel differences among countries, the oxidative ratio \(\text{OR}\)—the number of O\textsubscript{2} moles consumed per mole of CO\textsubscript{2} emitted, \(\left(x + \frac{1}{4}y\right)\)—can exhibit spatial and temporal variations (Steinbach et al., 2011). In this study, the carbon emitted by each type of fossil fuels in each grid is derived from the PKU-CO\textsubscript{2} data and used to calculate \(\text{OR}_i\) (where index \(i\) indicates the fuel type) for each grid. We use the ensemble mean of CDIAC, ODIAC, EDGAR, and PKU-CO\textsubscript{2} for carbon emission data (\(E_{\text{FF}}\)). Based on the equation below, the O\textsubscript{2} flux by fossil fuel can thus be estimated:

\[
C_{\text{FF}} = E_{\text{FF}} \times \text{OR} \times \frac{M_{O_2}}{M_C}, \tag{2}
\]

where \(C_{\text{FF}}\) is the annual O\textsubscript{2} flux (Gt O\textsubscript{2} yr\textsuperscript{−1}) per grid; \(E_{\text{FF}}\) is the carbon emissions from fossil-fuel combustion (Gt C yr\textsuperscript{−1}) per grid; \(M_{O_2}\) is the relative molecular mass of O\textsubscript{2} (32 g mol\textsuperscript{−1}); \(M_C\) is the relative molecular mass of carbon (12 g mol\textsuperscript{−1}); and OR is the molar ratio O\textsubscript{2}/CO\textsubscript{2} per grid at the time of burning. OR is calculated based on the following equation:

\[
\text{OR} = \frac{\sum_{i=1}^{4} E_{\text{FF},i} \times \text{OR}_i}{E_{\text{FF}}}, \tag{3}
\]

where again, \(i\) indicates the fuel type.

The OR of each fuel type is presented in Table 2, with a 90% confidence interval. We consider four fuel types: solid fuel (coal), liquid fuel (oil), gas fuel (natural gas), and biomass. The ORs for solid, liquid, and gas fuels are calculated after Keeling (1988), and that for biomass is based on Steinbach et al. (2011), with an assumed confidence interval of 0.03. In the PKU-CO\textsubscript{2} data, emissions from the flared gas are integrated into gas fuel ones. These two types of emissions have similar ORs (1.98 for flared gas and 1.95 for gas, respectively). For simplicity, we make the assumption that their ORs are equal.

2.1.2 \(O_2\) fluxes due to human respiration

The estimation of \(O_2\) fluxes due to human respiration is derived from the population density and daily total energy expenditure (TEE). Population densities of males and females are spatially distributed in the following way. The coarse-scale country totals of males and females from the 2019 Revision of World Population Prospects (United Nations et al., 2019) are mapped onto a 1.0° × 1.0° grid by using the spatial distribution of population density from Murakami and Yamagata (2019).

Jones (2003) estimated that for survival the daily \(O_2\) consumption for an astronaut is about 0.84 kg \(O_2\) day\textsuperscript{−1}.

Table 2. The oxidative ratio (OR) for each fuel type

| Fuel type              | \(O_2/CO_2\) molar ratio |
|------------------------|-------------------------|
| Solid fuel (coal)      | 1.17 ± 0.03             |
| Liquid fuel (oil)      | 1.44 ± 0.03             |
| Gas fuel (natural gas) | 1.95 ± 0.04             |
| Flared gas             | 1.98 ± 0.07             |
| Biofuel                | 1.07 ± 0.03             |
We estimate the daily $O_2$ consumption based on daily TEE (Walpole et al., 2012), defined as the product of basal metabolic rate (BMR) and physical activity level (PAL). BMR is determined by a variety of factors, including the sex, age, and weight. The BMRs at different ages are listed in Table 3 (Henry, 2005). The percentage of population at different age groups is calculated based on the 2019 Revision of World Population Prospects (United Nations et al., 2019). The weighted averages of BMRs in different age groups for males and females are calculated to obtain TEEs of males and females with moderate activity levels (PAL of 1.76 ± 0.1 for males and 1.64 ± 0.1 for females), and the TEEs are 9.69 and 7.85 MJ day$^{-1}$, respectively. To convert TEE to $O_2$ consumption, the average value of $O_2$ thermal equivalent (20.2 kJ L$^{-1}$ $O_2$, usually varies by the individual diet) is used (Dintenfass et al., 1983; Frappe, 2008). On this basis, $O_2$ consumption values of men and women are 0.69 and 0.55 kg day$^{-1}$, lower than that estimated for an astronaut. This is because the elderly and children, who consume less $O_2$ than young adults, are taken into account. We estimate the total $O_2$ consumption due to human respiration with the formula below:

$$C_{RES-H} = \frac{(P \times BMR \times PAL)_{male} + (P \times BMR \times PAL)_{female}}{TEO} \times \rho_{O_2} \times 365,$$

where $C_{RES-H}$ denotes the $O_2$ consumed by human breathing annually (Gt $O_2$ yr$^{-1}$); $P_{male}$ and $P_{female}$ are the total male and female populations of each grid, respectively; TEO is the thermal equivalent of $O_2$; and $\rho_{O_2}$ is the atmospheric $O_2$ density (1.429 g L$^{-1}$ at standard atmospheric temperature and pressure).

2.1.3 $O_2$ fluxes due to livestock respiration

On the basis of the gridded data of livestock population with a resolution of 0.083° [Gridded Livestock of the World (GLW 3); Gilbert et al., 2018], in which the global population densities of eight types of livestock (buffaloes, cattle, chickens, ducks, goats, horses, pigs, and sheep) are provided, $O_2$ consumption due to livestock respiration is estimated. In the areal-weighted version of this data set, animal numbers are evenly distributed in areas where the censuses are conducted for each type of livestock.

The mammal BMR can be estimated by the equation $BMR = 3.43M^{0.75}$ (Kleiber, 1932), in which $M$ is the mass of the mammal (g). Thus, calculations of the annual $O_2$ consumption by livestock can be done according to the formula below:

$$C_{RES-L} = \sum_{i=1}^{6} P_i \times BMR_{di} \times PAL \times LS_i,$$

where $C_{RES-L}$ represents the $O_2$ consumed by livestock annually (Gt $O_2$ yr$^{-1}$); $P_i$ denotes the total number of livestock of type $i$; $BMR_{di}$ refers to the average daily $O_2$ consumption by livestock of type $i$ (kg $O_2$ day$^{-1}$); PAL is the physical activity level (1.2 ± 0.1); and $LS_i$ is the lifespan of livestock of type $i$ (see Table 4).

The data derived from GLW 3 are in 2010. When the population increases, the livestock and agriculture industry should be developed to meet the growing food demand. In addition, we compared the time series of population and global total number of cattle (data from http://www.fao.org/faostat/en/#home) and found that the variation pattern of population is basically consistent with that of cattle. Therefore, when $O_2$ consumptions for other years are calculated, it is assumed that the number of livestock increase (decrease) with the increase (decrease) in human population at the same scale, and the geographical distribution of original data of livestock is maintained.

2.1.4 $O_2$ fluxes due to wildfires

By converting from the carbon emission data in the GFED v4 (van der Werf et al., 2017) from 1997 to 2018 with a spatial resolution of 0.25°, the $O_2$ consumption due to wildfires is obtained. Wildfire types are classified into six ones (see Table 1). According to the equation below, wildfire $O_2$ consumption can be obtained:

$$C_{FIRE} = M_{O_2} \times \sum_{i=1}^{6} \frac{DM \times contr_i \times EF_i \times \alpha_B}{M_{CO_2}},$$

where $C_{FIRE}$ is the wildfire $O_2$ consumption (Gt $O_2$ yr$^{-1}$); subscript $i$ is used to indicate the fire type; DM is the mass of dry matters emitted (kg DM m$^{-2}$ yr$^{-1}$); $contr_i$ is

| Table 3. BMRs at different age groups |
|--------------------------------------|
| Age | Percentage of population (%) | Male | Female |
|----|-----------------------------|------|--------|
| 0–3 | 6.5 | 6.30 ± 3.20 | 6.70 ± 3.40 | 1.47 ± 0.86 | 1.54 ± 0.87 |
| 3–10 | 16.4 | 21.40 ± 5.14 | 23.60 ± 6.14 | 4.17 ± 0.58 | 4.10 ± 0.63 |
| 10–18 | 17.3 | 40.00 ± 12.48 | 43.40 ± 12.91 | 5.51 ± 1.11 | 5.20 ± 0.80 |
| 18–30 | 14.4 | 61.00 ± 11.40 | 53.20 ± 10.04 | 6.31 ± 1.00 | 5.24 ± 0.79 |
| 30–60 | 32.3 | 65.30 ± 12.98 | 59.10 ± 13.65 | 6.35 ± 1.03 | 5.31 ± 0.80 |
| 60+ | 13.2 | 71.30 ± 14.94 | 60.00 ± 14.52 | 6.17 ± 1.09 | 4.93 ± 0.78 |
the contribution of dry matter emitted for fire of type $i$ (dimensionless); $EF_i$ is the emission factor of $CO_2$ (kg g$^{-1}$) of each fire of type $i$; and $\alpha_B$ is the molar ratio of $O_2/CO_2$ (1.1 ± 0.1).

The net effect of wildfires on the carbon/O$_2$ cycle is debated since burning of biomass is believed to be carbon neutral. However, biomass burning can also be carbon negative or carbon sources, depending on both the amount of $CO_2$ removed from or released into the atmosphere during its growth and the amount of $CO_2$ released when it is burned (Tilman et al., 2006). Therefore, it is still necessary to consider the wildfire components when investigating the O$_2$ cycle.

2.1.5 $O_2$ fluxes due to other human-related processes

Apart from the above-mentioned processes that may consume atmospheric O$_2$, non-fossil-fuel anthropogenic processes including chemical [ammonia (NH$_3$) production, nitric acid production, etc.] and metal industries (iron and steel production, etc.) can also consume O$_2$. However, almost all the non-fossil-fuel processes have been covered in the EDGAR inventory, which is averaged with other data sources of $CO_2$ emissions. Therefore, our estimation contained the non-fossil-fuel processes that may also consume atmospheric O$_2$. The global total $CO_2$ emissions in EDGAR is only about 1.5 Gt yr$^{-1}$ higher than the rest of the three datasets, which proves that the contribution from non-fossil-fuel processes is very small. Furthermore, following IPCC (2006), in which the stoichiometry ratios of related chemical reactions are provided, ORs of these processes are significantly lower than those listed in Table 2. Take the NH$_3$ production for example: the production of every 1 mol of NH$_3$ emits 0.44 mol CO$_2$ and consumes 0.26 mol O$_2$, with an OR of 0.59. For the metal production, the emission of CO$_2$ comes from the oxidation of coke, which is one type of fossil fuels listed in Table 2. Therefore, the consumption of O$_2$ in non-fossil-fuel processes has been covered in this paper. Considering that EDGAR is the only data set that includes these processes, we tripled the weight of EDGAR data when calculating the average (3 for EDGAR and 1 for the other three data sources).

The oxidation of atmospheric pollutants (e.g., photochemical pollutants, etc.) is also believed to influence the O$_2$ in the atmosphere. However, concentrations of the major atmospheric pollutants are at part-per-billion (ppb) or part-per-trillion (ppt) levels. The complete oxidation of these chemicals is only able to cause an O$_2$ disturbance at their corresponding magnitudes and may not influence the O$_2$ variation at the ppm level. Despite of the existence of oxidation processes in the atmosphere, changes in the O$_2$ concentration due to these processes (at ppb or ppt levels) may not be detected on large spatial scales due to the large background value of O$_2$. Take one of the major pollutants, N$_2$O, for example: the total emission of N$_2$O due to human activities (including the fossil-fuel combustion and chemical industries) to the atmosphere in 2012 was $9.15 \times 10^{12}$ Gt (Janssens-Maenhout et al., 2019). Even if we assume that all the elementary O$_2$ in N$_2$O comes from the atmosphere, only $3.3 \times 10^{13}$ Gt O$_2$ is consumed annually. If all the N$_2$O emitted by humans is oxidized in the atmosphere, only about $10^{13}$ GtO$_2$ will be removed. Therefore, the oxidation of chemical pollutants in the atmosphere is not considered in this paper.

2.2 Uncertainties in O$_2$ fluxes based on Monte Carlo simulations

We estimate uncertainties in our O$_2$ flux calculations by using an Monte Carlo ensemble simulation. For each grid, 1000 pseudo-random samples of input data are generated according to the probability density function (PDF) specified for each input. For the fossil-fuel consumption, uncertainties lie in $E_{FF}$ and OR. We assume that $E_{FF}$ has a normal distribution with a standard deviation based on discrepancies between the datasets, and

| Livestock | Body weight (kg) | Individual respiratory O$_2$ consumption (kg O$_2$ yr$^{-1}$) | Annual respiratory O$_2$ consumption in 2018 (kg O$_2$ yr$^{-1}$) |
|-----------|-----------------|-------------------------------------------------|-------------------------------------------------|
| Buffaloes | 272 ± 30        | 613.68 ± 71.33                                   | 1.31 ± 0.14 × 10$^{11}$                           |
| Cattle    | 272 ± 30        | 613.68 ± 71.33                                   | 1.00 ± 0.11 × 10$^{12}$                           |
| Chicken$^1$ | 0.862 ± 0.1     | 1.01 ± 0.17                                      | 2.34 ± 0.06 × 10$^{10}$                           |
| Ducks$^2$ | 0.862 ± 0.1     | 1.01 ± 0.17                                      | 1.90 ± 0.29 × 10$^{09}$                           |
| Goats     | 36 ± 3          | 134.66 ± 13.95                                   | 1.46 ± 0.14 × 10$^{11}$                           |
| Horses    | 260 ± 30        | 593.26 ± 49.81                                   | 4.15 ± 0.32 × 10$^{10}$                           |
| Pigs$^2$  | 75 ± 10         | 115.16 ± 16.42                                   | 1.29 ± 0.13 × 10$^{11}$                           |
| Sheep     | 30 ± 3          | 117.45 ± 13.04                                   | 1.49 ± 0.19 × 10$^{11}$                           |
| Total     |                 |                                                   | 2.48 ± 0.16 × 10$^{12}$                           |

$^1$ We assume that the life span of poultry (chickens and ducks) is 45 ± 5 days.

$^2$ We assume that the life span of a pig is 180 ± 10 days.
that OR also has a normal distribution with a 90% confidence interval (see Table 2).

For human respiration, the main uncertainty lies in the estimation of daily O$_2$ consumption, specifically, BMR and TEO. The standard deviation of BMRs for males and females in different age groups are presented in Table 3. In addition, we added a standard deviation of 2% in the percentage of population at each age group. For TEO, the standard deviation is set at 0.2 kJ L$^{-1}$ O$_2$.

The uncertainty in livestock respiration comes from the estimation of gridded population ($P$), BMR, PAL, and LS. Population data are based on census data, and the gridded population totals equal the total number of animals registered in the Food and Agriculture Organization of the United Nations (FAO) database (Gilbert et al., 2018). It is difficult to quantify the total population uncertainty, therefore we consider only the uncertainties in BMR, PAL, and LS, as listed in Table 4.

The uncertainty in wildfire calculations lies in the estimated DM, contr, EF$_i$, and $\alpha_B$. van der Werf et al. (2017) pointed out that due to the difficulty in assessing uncertainties in the various fuel layers, they refrained from estimating the formal uncertainties. If present, these uncertainties may far exceed those in GFED v3 (the previous version of the dataset used here). Therefore, we consider only the uncertainties in EF$_i$ (provided on the GFED website) and $\alpha_B$ (1.1 ± 0.1).

Furthermore, uncertainties due to different time ranges among the datasets, and inconsistency within the datasets may also exist. For example, the CDIAC data are only updated to 2013 while the EDGAR data are updated to 2018. The GFED data have failed to maintain the uncertainty of datasets since 2017 because the burned area data have been upgraded by using a different method. Thus, in order to update our results to the latest year, two versions of our data (the official and beta versions) are prepared. The official version is updated to 2013, with all of the data sources listed in Table 1. The beta version is updated to 2017, in which the data of PKU-CO$_2$ and CDIAC are not included. The beta version may have not maintained the consistency since 2013 due to the lack of data sources. In the following sections, the beta version of our data is analyzed.

3. Results

3.1 Estimation of O$_2$ fluxes due to fossil-fuel combustion

It has been generally accepted that the fossil-fuel combustion has made the largest contribution to the atmospheric O$_2$ decline in the past decades (Valentino et al., 2008; Keeling and Manning, 2014; Martin et al., 2017).

Figures 1a and b show the distribution of O$_2$ fluxes due to the fossil-fuel combustion and corresponding OR respectively for 2018. In Fig.1a, the distribution of O$_2$ consumption is similar to that of the CO$_2$ emission. The US, Europe, India, and East Asia are identified as the high O$_2$ consumption regions (with O$_2$ fluxes greater than 500 g O$_2$ m$^{-2}$ yr$^{-1}$), while Africa, Australia, and South America are identified as the low areas. As for the distribution of OR (Fig. 1b), the areas that display small ORs, indicating coal as a primary energy source, are located in South Africa, India, and East Asia, while large ORs (larger than 1.45), implying that the natural gas is regarded as the primary energy source, are located in Russia, central Asia, Canada, and most areas of South America. The highest O$_2$ fluxes appear over China, the US, India, and Russia. The spatial distribution of OR is basically consistent with that in Steinbach et al. (2011).

The global trend in O$_2$ consumption is presented in Fig. 2a, where areas covered by warm and cold colors denote the increased and decreased consumptions respectively. The consumption is increasing mainly in Asia, whereas in Europe it shows a downward trend. Figure 2b displays the trend in OR of each grid. Areas including Argentina, Russia, and Europe show an increas-
ing trend while regions such as East Asia and North America show a downward trend. The global total O\textsubscript{2} consumption by fossil fuel increased from 16.6 ± 1.0 to 38.7 ± 0.43 Gt between 1975 and 2018 (Fig. 3).

3.2 Estimation of O\textsubscript{2} fluxes due to human and livestock respiration

In the calculation of O\textsubscript{2} fluxes due to human breathing, a moderate PAL of 1.76 is assumed for both males and females. For livestock, we consider eight different types: buffaloes, cattle, chickens, ducks, goats, horses, pigs, and sheep, with a PAL of 1.2. The BMR change due to internal (exercise and diets) and external factors (ambient temperature variation) are not considered (Cai et al., 2018). In this case, true O\textsubscript{2} fluxes due to livestock and humans are likely to be higher than what we estimate here. The global distribution and long-term trends in O\textsubscript{2} fluxes due to human breathing are presented in Fig. 4. The largest O\textsubscript{2} flux (up to 200 g O\textsubscript{2} m\textsuperscript{-2} yr\textsuperscript{-1}) can be found in India and North China, where the largest population density is located. During the past 30 years, the global population has witnessed significant growth, especially in Asia, resulting in an increase in the O\textsubscript{2} consumption there.
global total volume, the O\textsubscript{2} consumption due to livestock (2.48 ± 0.16 Gt O\textsubscript{2} yr\textsuperscript{-1}) is slightly larger than that due to human respiration (1.73 ± 0.13 Gt O\textsubscript{2} yr\textsuperscript{-1}) in 2018 (see Fig. 6 and Table 4). Among the eight types of livestock considered in this study, cattle and buffaloes consumed the highest volume of O\textsubscript{2}, about 46% of the total O\textsubscript{2} consumption by livestock.

### 3.3 Estimation of O\textsubscript{2} fluxes due to wildfires

The spatial pattern of O\textsubscript{2} fluxes due to wildfires in 2018 is shown in Fig. 7. The highest consumption occurs mainly in the tropics, especially central Africa. This is because abundant surface vegetation exists in these areas, leading to a high value of net primary productivity (NPP). In other words, when wildfires occur in these areas, a higher volume of carbon is released into the atmosphere, which also causes larger O\textsubscript{2} fluxes in the meantime. The global mean O\textsubscript{2} consumption by wildfires is 5.87 Gt O\textsubscript{2} yr\textsuperscript{-1} and displays a weak decline in the period 1997–2018, with a maximum of 7.97 ± 0.8 Gt O\textsubscript{2} yr\textsuperscript{-1} in 1997 and a minimum of 4.82 ± 0.5 Gt O\textsubscript{2} yr\textsuperscript{-1} in 2013. Of the various wildfire types (Fig. 8), savanna fires cover the largest areas around the world and cause the highest O\textsubscript{2} flux, contributing more than 60%; the next-largest O\textsubscript{2} flux is contributed by wildfires in the tropical forests.

### 3.4 O\textsubscript{2} balance of the terrestrial ecosystem

Figure 9 shows the global distribution of averaged net terrestrial O\textsubscript{2} flux from 2000 and 2018. The distribution of O\textsubscript{2} flux (Fig. 9a) has a basically identical pattern to that of O\textsubscript{2} flux due to the fossil fuel. The reason is quite obvious. Among the four O\textsubscript{2} processes considered in this paper, burning of fossil-fuel causes the highest O\textsubscript{2} flux. Additionally, the high fossil-fuel flux is mainly concentrated in regions where a high density of livestock and humans are located. The following regions are areas where the highest O\textsubscript{2} flux occurs: East Asia, India, North America, Europe, and central Africa. Normally, these areas should all be relatively developed areas with dense populations and intense human activities. However, situations are different in central Africa, an underdeveloped
region where wildfires make the biggest contribution to local O\textsubscript{2} fluxes, which also displays a high level of the O\textsubscript{2} flux. The areas that cover Australia, the Tibetan Plateau, the Sahara Desert, and the Amazon rainforest are identified as the low O\textsubscript{2} consumption areas.

Estimation of the net biological O\textsubscript{2} flux over land is based on the result of Net Ecosystem Exchange (NEE) provided by the NOAA CarbonTracker, version CT2017 (from 2000 to 2016) and CT-NRT.v2019-2 (from 2017 to 2018; Peters et al., 2007). The O\textsubscript{2} flux caused by fire activities, which has been considered in the previous section in this paper, are excluded from NEE estimates. Areas with the negative flux (covered by brown colors, O\textsubscript{2} sink) denotes places where the land is consuming O\textsubscript{2} in the atmosphere, while areas with the positive flux (covered by green colors, O\textsubscript{2} source) indicate places where O\textsubscript{2} is produced. The global pattern of averaged net terrestrial O\textsubscript{2} flux averaged from 2000 to 2018, namely the result of NEE flux minus human-related flux, is shown in Fig. 9b. Since the positive O\textsubscript{2} flux from land is much smaller in magnitude than the negative flux, a modification of the color bar has been carried out so that the visualization is enhanced. Brown regions (East Asia, Europe, North America, and northern South America) indicate that human activities consume more O\textsubscript{2} than the local ecosystem’s supply ability. The brown regions have occupied more than 50% of the global land surface. Green regions, including the Tibetan Plateau, northern Canada, and Siberia, represent regions that are still able to release O\textsubscript{2} to the atmosphere in spite of the local anthropogenic forcing.

At present, because of the worldwide intensification of energy consumption, population growth, overgrazing, etc., the human-related O\textsubscript{2} flux has been far greater than the terrestrial ecosystem’s supply ability. Thus, the O\textsubscript{2} balance has already been disturbed, resulting in a steady decrease in the atmospheric O\textsubscript{2} concentration in the past decades. According to our estimation, it is revealed that during the period of 2000–2018, the O\textsubscript{2} consumption has experienced an increase from 33.69 ± 1.11 Gt O\textsubscript{2} yr\textsuperscript{-1} in 2000 to 47.63 ± 0.80 Gt O\textsubscript{2} yr\textsuperscript{-1} in 2018, whereas the land production (11.34 ± 13.48 Gt O\textsubscript{2} yr\textsuperscript{-1} averaged during the period from 2000 to 2018) has only increased slightly (Fig. 10).

With regards to the O\textsubscript{2} flux between the atmosphere and ocean, a hypothesis has already been widely accepted that the ocean might play a role as the O\textsubscript{2} source (positive flux) in the O\textsubscript{2} cycle. The climate change characterized by global warming has cut down the solubility of surface seawater (Bopp et al., 2002; Plattner et al., 2002), which directly results in a declining dissolved O\textsubscript{2} in the upper ocean. Thus, O\textsubscript{2} reserved in the ocean is gradually being released to the atmosphere. The exchange of O\textsubscript{2} between the air and sea is thought to be superimposed on the air–sea O\textsubscript{2} flux in the natural background of different timescales. It has been estimated that during the period of 2000–2010 the amount of O\textsubscript{2} outgassed from oceans was 1.4 Gt O\textsubscript{2} yr\textsuperscript{-1} (Keeling and Manning, 2014). Compared with the magnitude of other processes in the budget we proposed, this value is small enough to be ignored. In addition, the sparse coverage of observations over the ocean makes it challenging to provide a spatial distribution of air–sea O\textsubscript{2} with acceptable accuracy and reliability (Keeling et al., 2010).

3.5 Uncertainty analysis and data validation

Monte Carlo simulations were carried out to estimate uncertainties in the O\textsubscript{2} consumption for each component we calculated (see Section 2.2). The standard deviation in the total O\textsubscript{2} consumption flux in 2018 is 0.67 Gt O\textsubscript{2} yr\textsuperscript{-1}. Standard deviations (absolute uncertainty) and coefficients of variation (relative uncertainty) of the spatial distribution are shown in Fig. 11. Regions with a large standard deviation (greater than 200 g O\textsubscript{2} m\textsuperscript{2} yr\textsuperscript{-1}) are consistent with those with high O\textsubscript{2} consumption (East Asia, India, Europe, and North America). Regions with a
small standard deviation (less than 10 g O$_2$ m$^{-2}$ yr$^{-1}$) are consistent with those with low O$_2$ consumption (north of the Sahara Desert and Tibetan Plateau).

However, in terms of the relative uncertainty, large coefficients of variation (greater than 100%) are mainly found in regions with low O$_2$ flux (high-latitude areas in the Northern Hemisphere, north of the Sahara Desert, central Asia, and Southeast Asia). In areas with high O$_2$ consumption flux (East Asia, India, Europe, and North America), the coefficient of variation is mostly less than 30%. Our estimates exhibit better credibility in regions with high O$_2$ flux, implying that the main contributors are well captured in our estimates. More work is needed to reduce uncertainties in the regions with low O$_2$ consumption flux.

For validation, we compared the observed annual changes in atmospheric O$_2$ with the estimated annual changes based on O$_2$ consumption fluxes at the global scale from 1997 to 2018. The estimated annual change ($\Delta$O$_2$, Gt O$_2$ yr$^{-1}$) is calculated according to the following equation:

$$\Delta O_2 = -C_{\text{anthro}} + P_{\text{land}} + O_{\text{ocean}},$$

where $C_{\text{anthro}}$ (Gt O$_2$ yr$^{-1}$) is the O$_2$ consumption due to anthropogenic activities (excluding wildfires); $P_{\text{land}}$ (Gt O$_2$ yr$^{-1}$) and $O_{\text{ocean}}$ (Gt O$_2$ yr$^{-1}$) denote the net O$_2$ production from the land by photosynthesis and outgassing from the ocean, respectively. $P_{\text{land}}$ and $O_{\text{ocean}}$ are estimated based on the method used by Ishidoya et al. (2012), Tohjima et al. (2008), and Bender et al. (2005). The results indicate an average production of 10.14 Gt O$_2$ yr$^{-1}$ from the land and outgassing of 0.89 Gt O$_2$ yr$^{-1}$ from the ocean during the period 1997–2018. Figure 12a shows a comparison of the observed annual changes in O$_2$ (Keeling, 2019) and estimated annual changes. The observed global annual changes were calculated by using weighting functions according to the latitude of each station. The results have a correlation coefficient of 0.82 at the 99% confidence level and a regression coefficient of 1.16 with an intercept of $-5.17 \pm 9.85$.

Figure 12b shows the difference between the estimated and observed annual changes in O$_2$ (estimated minus observed) during 1997–2018. The observed declines are faster than estimated changes before 2004, and slower after 2004. This may be explained by an underestimation of anthropogenic fluxes or overestimation of the O$_2$ production from land and ocean before 2004. Changes in the land production may be correlated with internal climate variabilities, such as the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Further studies are required to elucidate impacts of the climate variability and human activities on the response of global O$_2$ cycles at both regional and global scales.

4. Future projections

In future scenarios, human activities will still play an
important role in modulating the global O<sub>2</sub> cycle. Here, we made an initial attempt to project the O<sub>2</sub> consumption in future scenarios based on the emission trajectories of CO<sub>2</sub> throughout the end of the 21st century. Four of the shared socioeconomic pathways (SSPs) used in the Coupled Model Intercomparison Project Phase 6 (CMIP6; Gidden et al., 2019) and four of the representative concentration pathways (RCPs) are selected in our estimations. From Fig. 13, we can see a significant increase in the O<sub>2</sub> consumption in RCP8.5 and SSP5-8.5, with the O<sub>2</sub> consumption higher than 100 Gt at the end of the 21st century. While in RCP2.6 and SSP1-2.6, negative fluxes will occur in the mid-2070s due to the popularization of biofuels. Biofuels can be carbon negative, which captures CO<sub>2</sub> from the atmosphere higher than that released during its production and combustion. Therefore, during the carbon sequestration via photosynthesis, O<sub>2</sub> is released into the atmosphere. It is, however, to be noted that OR is assumed to be independent of time (a constant value of 1.4, the current global average) in the estimation. In future scenarios, fuel types may vary when renewable energy is introduced and even becomes a dominant energy type. Here, we only present a rough estimation, which deserves further investigations in the future.

5. Conclusions and discussion

In this paper, a global dataset of the O<sub>2</sub> consumption on the grid scale is developed and compared with the biological O<sub>2</sub> flux to reveal the geographical location of the source and sink of atmospheric O<sub>2</sub>. To our knowledge, this dataset is the first global map of O<sub>2</sub> consumption. The uncertainty is estimated based on the Monte Carlo method. The estimated dataset is also compared with observations for validation. The result indicates an increase in the O<sub>2</sub> consumption flux from 33.69 ± 1.11 Gt O<sub>2</sub> yr<sup>−1</sup> in 2000 to 47.63 ± 0.80 Gt O<sub>2</sub> yr<sup>−1</sup> in 2018. The combustion of fossil fuel and industrial activities (38.45 ± 0.61 Gt O<sub>2</sub> yr<sup>−1</sup>) contribute the most, followed by wildfires (4.9 ± 0.48 Gt O<sub>2</sub> yr<sup>−1</sup>) and respiration processes by livestock and humans (2.48 ± 0.16 and 1.73 ± 0.13 Gt O<sub>2</sub> yr<sup>−1</sup>, respectively). The US, Europe, India, and East Asia are identified as the high O<sub>2</sub> consumption regions (with O<sub>2</sub> fluxes greater than 500 g O<sub>2</sub> m<sup>−2</sup> yr<sup>−1</sup>), while Australia, the Tibetan Plateau, the Sahara Desert, and the Amazon rainforest are identified as the low O<sub>2</sub> consumption areas. The O<sub>2</sub> sink regions (East Asia, Europe, North America, and northern South America) occupy more than 50% of the global land surface, while the O<sub>2</sub> source regions are mainly distributed in the Tibetan Plateau, northern Canada, and Siberia.

This dataset can be further improved by compiling other fuel-consumption data from different data sources. We also need to consider other potential impacts, including the climate and diet, on calculations of human and
livestock respiration. The updated data with a higher temporal resolution, including seasonal, weekly, and daily cycles for different fuel types, are also needed, so that monthly observations can be used for further validation.

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