Science Bulletin 63 (2018) 1180–1186

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Article

# The global oxygen budget and its future projection

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ARTICLE INFO

*Article history:*
Received 12 July 2018
Received in revised form 20 July 2018
Accepted 24 July 2018
Available online 3 August 2018

*Keywords:*
Atmospheric oxygen
Oxygen decline
Oxygen budget
Oxygen concentration

ABSTRACT

Atmospheric oxygen ($O_2$) is the most crucial element on earth for the aerobic organisms that depend on it to release energy from carbon-based macromolecules. This is the first study to systematically analyze the global $O_2$ budget and its changes over the past 100 years. It is found that anthropogenic fossil fuel combustion is the largest contributor to the current $O_2$ deficit, which consumed 2.0 Gt/a in 1900 and has increased to 38.2 Gt/a by 2015. Under the Representative Concentration Pathways (RCPs) RCP8.5 scenario, approximately 100Gt (gigatonnes) of $O_2$ would be removed from the atmosphere per year until 2100, and the $O_2$ concentration will decrease from its current level of 20.946% to 20.825%. Human activities have caused irreversible decline of atmospheric $O_2$. It is time to take actions to promote $O_2$ production and reduce $O_2$ consumption.


## 1. Introduction

$O_2$ is the most crucial atmospheric component for lives on earth, which is maintained not only by the process of photosynthesis by green plants and algae but also the processes that consume $O_2$, such as respiration, combustion and decomposition [1]. Observations [2] have revealed that with the rapid development of industrialization and modern civilization, the concentration of atmospheric $O_2$ has been declining over the past 30 years. Simultaneously, the $O_2$ levels in oceans have also been decreasing due to the change of solubility under the back ground of global warming [3], and more dead zones have appeared [4].

Comparing to the rapid increase of $CO_2$ concentration and its climate impacts, the decline of atmospheric $O_2$ is far beyond the focus of research community and policy makers due to its negligible changes compared to its massive inventory in the Earth's atmosphere. In fact, the decline in atmospheric $O_2$ should be much more addressed [5] since it could affect the survival of humans and most of the species directly. Here, based on observations [6] and Fifth Coupled Model Intercomparison Project (CMIP5) simulations [7], this study diagnoses the global $O_2$ budget systematically to provide a clear understanding of $O_2$ decline.

## 2. Data and methods

In this section, some important issue involved in our research is discussed, including definitions of several terms commonly used in atmospheric $O_2$ work, the method of estimating the consumption and production of $O_2$ and the construction of global $O_2$ cycle.

### *2.1. The observational oxygen concentration data*

Typically, the concentrations of gas are reported in the unit of volume fraction (e.g., ppm, ppb, etc.). However, the concentration of atmospheric $O_2$ are reported as changes in the $O_2/N_2$ ratio of air relative to a reference (air collected in the mid-1980s) to avoid the non-negligible interference caused by dilution effects. The observed changes are very small and are reported in per meg units [8]:

$$\delta = ((O_2/N_2)_{sample} - (O_2/N_2)_{reference})/(O_2/N_2)_{reference}) \times 10^6, \quad (1)$$

where the subscripts "sample" and "reference" indicate the sample air and the reference air, respectively. The changes observed in the $O_2/N_2$ ratio are very small. One per meg equals $10^{-4}$ percent, or $10^{-6}$. The $O_2$ in air of 2016 had a value of approximately −600 per meg, which means that 0.06% of the $O_2$ had been removed from the atmosphere and that the $O_2$ volume concentration in 2016 was 99.94% of the concentration in the mid-1980s. The conversion from per meg to ppm and Gt is expressed by the following formula: 1 per meg = 0.20946 ppm = $M \times 10^{-6} \times 32$ g/mol $O_2$ = 1.186 Gt $O_2$, where

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https://doi.org/10.1016/j.scib.2018.07.023
2095-9273/

$M = 3.706 \times 10^{19}$ mol is a reference value for the total number of $O_2$ molecules in the atmosphere.

Observational $O_2$ concentration data of nine stations around the world from the Scripps $O_2$ Program (http://scrippso2.ucsd.edu/) is used in this study. These data are from remote locations or other locations situated so that they represent averages over large portions of the globe rather than local background sources [6].

### 2.2. The estimation of oxygen consumption

$O_2$ is consumed by a wide range of processes, including (1) autotrophic respiration, (2) heterotrophic and soil respiration, (3) fires, (4) fossil fuel combustion and industry, (5) the weathering of organic matter and sulfide minerals, and (6) volcanic gas oxidation [9]. The main cause of the $O_2$ decrease in the atmosphere is fossil fuel combustion. Population growth and the growing number of livestock, which directly impacts human livelihoods, also contribute to the depletion of atmospheric $O_2$ by heterotrophic respiration. In addition, deforestation, tropical peatland fires, and the burning of agricultural waste not only contribute to the increase in atmospheric $CO_2$ but also remove a significant amount of $O_2$ from the atmosphere. Here we mainly discuss the following four processes, since the other processes are either hard to quantify or tiny enough to be neglected. All the data are gridded to a $1.0° \times 1.0°$ resolution for analysis.

#### 2.2.1. Oxygen consumption by fossil fuel combustion

The estimation of $O_2$ consumption by fossil fuel combustion is based on $CO_2$ emissions data from the Carbon Dioxide Information Analysis Center (CDIAC, http://cdiac.ess-dive.lbl.gov/). According to Keeling [9], about 1.4 mol of $O_2$ is consumed when 1 mol of $CO_2$ are emitted. For future projections of $O_2$ combustion, the global total carbon emission data under RCP4.5 and RCP8.5 from 2005 to 2100 is obtained from RCP scenario data group (http://www.pik-potsdam.de/~mmalte/rcps/).

#### 2.2.2. Human respiration

$O_2$ consumption by human respiration is based on the population density datasets from the Gridded Population of the World, Version 4 (GPWv4, http://sedac.ciesin.columbia.edu/). The population counts for the future scenario (SSP1 and SSP3) are provided by Murakami et al. [10]. We assume that an adult at rest consumes approximately 21 L of $O_2$ per hour and in a day, a man works 8 h with a labor intensity between light and medium (1.0 L $O_2$/min) and rests (21 L $O_2$/h) for the remaining 16 h. According to the standard above, an adult consumes approximately 1.17 kg (816 L) of $O_2$ per day.

#### 2.2.3. Livestock consumption

$O_2$ consumption by livestock respiration is based on the spatial distributions of main livestock from Gridded Livestock of the World v2.09 [11]. The basal metabolism rate (BMR) is the rate of energy expenditure per unit time by endothermic animals at rest and can be reported in mL $O_2$/min. The BMR (mL $O_2$/h) of a mammal can be predicted with the formula given by Kleiber [12], BMR = 3.43 $M^{0.75}$, where $M$ is the animal's mass (g). Following this formula, the annual $O_2$ consumption of the livestock can be estimated (Table 1). In the future projections and historical simulations, we assume that the total number of all livestock is proportional to the total human population.

#### 2.2.4. Fire

$O_2$ consumption by fire is based on the data on carbon emissions from fire activities derived from the Global Fire Emissions Database (GFED, http://www.globalfiredata.org) [13]. The GFED combines satellite information on fire activity and vegetation productivity to estimate gridded monthly burned area and fire emissions as well as scalars that can be used to calculate higher-temporal resolution emissions. The current version of this dataset is version 4, which has a spatial resolution of 0.25° and ranges from 1997 to 2016. $O_2$ consumption by fire is estimated assuming that the $O_2$:$CO_2$ molar ratio is 1.1. The consumption of $O_2$ by fire changes little annually, and we regard this value as constant (5.87 Gt/a) in the future scenarios and historical simulations.

### 2.3. Oxygen production by land

$O_2$ is produced during the processes of photosynthesis, in which the plants and other organisms absorb carbon dioxide ($CO_2$) from the atmosphere and release oxygen ($O_2$). The photosynthesis can be expressed by the following chemical equation:

$$6H_2O+6CO_2 \rightarrow C_6H_{12}O_6+6O_2. \tag{2}$$

Gross primary production (GPP) is the total amount of $CO_2$ fixed by a plant in photosynthesis. Net Primary Productivity (NPP) is the net amount of gross primary productivity remaining after including the costs of plant respiration [14–16]. The remaining fixed energy is referred to as net primary productivity (NPP). Net Ecosystem Productivity (NEP) refers to the net amount of primary productivity remaining after including the costs of respiration by plants, heterotrophs, and decomposers. Therefore, NEP = GPP − ($R_a + R_h + R_d$), where $R_a$ is the autotrophic respiration, $R_h$ is the respiration by heterotrophs and $R_d$ is the respiration by decomposers (microbes). A measure of NEP is of great interest when determining the $CO_2$ balance between various ecosystems, even the entire Earth, and the atmosphere. The $O_2$ balance is closely linked to the $CO_2$ balance.

According to Eq. (2), we can use the following equation to calculate the net amount of $O_2$ produced during the processes of photosynthesis with the known net carbon fixed (NEP).

$$O_2 = \mathrm{NEP} \times 2.667. \tag{3}$$

**Table 1**
Oxygen consumption by livestock respiration.

| Livestock | Total number (in 2006) | Mass (kg) | Daily oxygen consumption (g/d) | Total annual oxygen consumption (in 2006) (Gt/a) |
|---|---|---|---|---|
| Cattle | $1.40 \times 10^9$ | 750.0 | 2989.27 | 1.52 |
| Chickens[a] | $1.98 \times 10^{10}$ | 1.5 | 25.72 | 0.18 |
| Ducks[b] | $2.21 \times 10^9$ | 1.7 | 29.15 | 0.02 |
| Goats | $9.37 \times 10^8$ | 90.0 | 609.47 | 0.21 |
| Pigs | $8.99 \times 10^8$ | 200.0 | 1109.28 | 0.36 |
| Sheep | $1.07 \times 10^9$ | 90.0 | 609.47 | 0.24 |
| Total | | | | 2.53 |

[a] Chickens and ducks are not mammals, $O_2$ consumption per hour is 750 mL for chickens and 850 mL for ducks.
[b] Africa and South America are excluded due to scarcity of observed data for duck.

**Table 2**
CMIP5 models and their variables used in this study (land part).

| Model | Institute | NEP[b] | | | NPP[b] | | | Rh[b] | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Historical | RCP4.5 | RCP8.5 | Historical | RCP4.5 | RCP8.5 | Historical | RCP4.5 | RCP8.5 |
| HadGEM2-CC | Met Office Hadley Centre, UK | √[c] | √ | √ | √ | √ | √ | | | |
| HadGEM2-ES | Met Office Hadley Centre, UK | √ | √ | √ | √ | √ | √ | | | |
| MIROC-ESM[a] | Japan Agency for Marine-Earth Science and Technology, Japan | | | | √ | √ | √ | √ | √ | √ |
| MIROC-ESM-CHEM[a] | Japan Agency for Marine-Earth Science and Technology, Japan | | | | √ | √ | √ | √ | √ | √ |
| GFDL-ESM2G[a] | Geophysical Fluid Dynamics Laboratory, USA | | | | √ | √ | √ | √ | √ | √ |
| GFDL-ESM2M[a] | Geophysical Fluid Dynamics Laboratory, USA | | | | √ | √ | √ | √ | √ | √ |
| NorESM1-M | Norwegian Climate Centre, Norway | √ | √ | √ | √ | √ | √ | | | |
| CanESM2 | Canadian Centre for Climate Modelling and Analysis, Canada | √ | √ | √ | √ | √ | √ | | | |
| CCSM4[a] | National Center for Atomspheric Research, USA | | | | √ | √ | √ | √ | √ | √ |

[a] MIROC-ESM, MIROC-ESM-CHEM, GFDL-ESM2M, GFDL-ESM2G, MPI-ESM-LR, MPI-ESM-MR and CCSM4 did not provide NEP results, so we calculated NEP by their NPP and Rh products.
[b] The monthly mean NEP, NPP and Rh (i.e. CMIP5 variable name: nep, npp and rh) products was calculated by the model by the unit of kg $m^{-2}$ $s^{-1}$, so we converted to kilograms of NEP, NPP and Rh per year by converting from months to annual and from seconds to year (×2592000) √.
[c] "√" indicates whether variables (oxygen flux, NEP, NPP, etc.) under different scenarios (historical, RCP4.5, RCP8.5, etc.) are output in these models. "Yes" is indicated by "√".

**Table 3**
CMIP5 models and their variables used in this study (ocean part).

| Model Name | Institute | Oxygen Flux[a] | | | Net Primary Production[b] | | |
|---|---|---|---|---|---|---|---|
| | | Historical | RCP4.5 | RCP8.5 | Historical | RCP4.5 | RCP8.5 |
| IPSL-CM5A-LR | Institut Pierre-Simon Laplace, France | √[d] | √ | √ | √ | √ | √ |
| IPSL-CM5A-MR | Institut Pierre-Simon Laplace, France | √ | √ | √ | √ | √ | √ |
| IPSL-CM5B-LR | Institut Pierre-Simon Laplace, France | √ | √ | √ | √ | √ | √ |
| CMCC-CESM[c] | Euro-Mediterranean Center on Climate Change, Italy | √ | | √ | | | |
| GFDL-ESM2G | Geophysical Fluid Dynamics Laboratory, USA | √ | √ | √ | √ | √ | √ |
| GFDL-ESM2M | Geophysical Fluid Dynamics Laboratory, USA | √ | √ | √ | √ | √ | √ |
| MRI-ESM1[c] | Meteorological Research Institute, Japan | √ | | √ | | | |
| MPI-ESM-LR | Max Planck Institute for Meteorology, Germany | √ | √ | √ | √ | √ | √ |
| MPI-ESM-MR | Max Planck Institute for Meteorology, Germany | √ | √ | √ | √ | √ | √ |
| HadGEM-CC | Met Office Hadley Centre, UK | √ | √ | √ | √ | √ | √ |
| HadGEM-ES | Met Office Hadley Centre, UK | √ | √ | √ | √ | √ | √ |

[a] Air-sea Oxygen Flux (i.e. CMIP5 variable name: fgo2) was calculated by the model in mol $m^{-2}$ $s^{-1}$, so we converted to grams of $O_2$ per year by converting from moles to gram (×32) and from seconds to year (×31536000).
[b] Oceanic Net Primary Production (i.e. CMIP5 variable name: intpp) was calculated by the model in mol $m^{-2}$ $s^{-1}$, so we converted to grams of carbon per year by converting from moles to gram (×12) and from seconds to year (×31536000).
[c] CMCC-CESM and MRI-ESM1 did not have RCP4.5 results, so they were excluded when calculating ensemble mean of oxygen flux in RCP4.5 and net primary production in all scenarios.
[d] "√" indicates whether variables (oxygen flux, NEP, NPP, etc.) under different scenarios (historical, RCP4.5, RCP8.5, etc.) are output in these models. "Yes" is indicated by "√".

The unit of $O_2$ production is g $m^{-2}$ $a^{-1}$. In this paper, the simulated *NEP* dataset from 1900 to 2100 is obtained from the simulation by CMIP5 models (Table 2) and are gridded to 1.0° × 1.0° resolution for analysis. Some models directly provide NEP while others provide NPP and $R_h$.

### 2.4. Air-sea oxygen flux

Ocean is another important source of atmospheric $O_2$. The CMIP5 models (Table 3) provide monthly mean air-sea $O_2$ flux in the unit of mol $m^{-2}$ $s^{-1}$. In this study, we convert the unit to g $m^{-2}$ $a^{-1}$ and grid the data to 1.0° × 1.0° resolution for analysis.

### 2.5. The oxygen budgets

The processes that release $O_2$ to the atmosphere (e.g., photosynthesis) and the processes that consume $O_2$ (e.g., respiration, fires, fossil fuel combustion, the weathering of organic matter, and volcanic oxidation) result in large fluxes of $O_2$ to and from the atmosphere and constitute the global $O_2$ cycle [1]. A slight disturbance in production or consumption can generate large shifts in atmospheric $O_2$ concentrations. Based on the discussion of production and human-related $O_2$ consumption in the previous sections, the global $O_2$ cycle is constructed.

$$D_{\mathrm{ATM}} = -C_{\mathrm{FF}} - C_{\mathrm{RES}} - C_{\mathrm{FIRE}} + P_{\mathrm{LAND}} + O_{\mathrm{OCEAN}} + \mathrm{Residual}, \tag{4}$$

where $D_{\mathrm{ATM}}$ is the rate of decline in global atmospheric $O_2$ concentrations; $C_{\mathrm{FF}}$, $C_{\mathrm{RES}}$, $C_{\mathrm{FIRE}}$ is the consumption of fossil fuel, humans and livestock and fire respectively. $P_{\mathrm{LAND}}$ and $O_{\mathrm{OCEAN}}$ represent the production from land and outgassing from the ocean. The equation above omits the respiration of wild animals, weathering of organic matter and volcanic oxidation, which are insignificant compared to the processes above and are hard to quantify. Thus, the residual term is introduced to correct this bias and is calculated based on the difference between the observational $D_{\mathrm{ATM}}$ and the simulated $D_{\mathrm{ATM}}$ from 1991 to 2005. All terms above are reported in Gt/a.

## 3. Results analysis

The four main processes including fossil fuel combustion, human and land livestock respiration, and fires, are presented in

Fig. 1. From 2000 to 2013, these four main processes removed approximately 41.82 Gt $O_2$ from the atmosphere per year. Up to 73.05% of this $O_2$ was removed by fossil fuel combustion (30.55 Gt), with high values observed in Eastern Asia, Europe and North America, which is still growing rapidly. Approximately 5.39 Gt/a $O_2$ is consumed by the breathing of human and land livestock; this value will continue to increase with the booming population and its growing food demand. Fire consumes approximately 5.88 Gt/a $O_2$, and this value changes little annually. Savanna fire accounts for more than 65% of all fires and is mainly distributed in equatorial Africa. The second-largest mechanism of fire-related consumption is tropical deforestation and degradation. Tropical forests in Amazon and Southeast Asia experience the most deforestation. Burning tropical rainforests not only removes a considerable amount of $O_2$ from the atmosphere and emits greenhouse gases, including $CO_2$ and $CH_4$, to the atmosphere, thus causing global warming [13], but also permanently reduces the global production of $O_2$ by photosynthesis, thus causing accelerating $O_2$ depletion.

The $O_2$ production over land could be quantified by the net ecosystem production (NEP), and the climatological distribution of NEP from CMIP5 simulation is presented in Fig. 2a. It shows that total amount of NEP is 5.28 Gt/a (equivalent to 14.08 Gt/a of $O_2$) and 72.2% is provided by the tropics. Under the RCP4.5 and RCP8.5 scenarios, the $O_2$ production from land rises to 16.75 Gt/a and 19.44 Gt/a, respectively, by the end of the 21st century, and the most rapid increase occurs in the tropics (Fig. 2b and c), especially in Central Africa and Southeastern Asia. The changes of NEP are mainly determined by the NPP (net primary production) variability, which is easier to be measured. Under climate change, the global NPP presents an increasing trend and the reason could be attributed to the following three aspects. Firstly, the increase of atmospheric $CO_2$ has a positive effect on NPP because atmospheric carbon is a driving factor for the photosynthesis of $C_3$ plants [17]. Secondly, nitrogen deposition can increase the biomass in nitrogen-limited northern temperate forests and result in an increase of the NPP [18,19]. Thirdly, global warming leads to the lengthening of the plant growing season [20] and the increasing of precipitation [21], which also exert positive effects on the increasing NPP. However, the $O_2$ increase caused by the above processes cannot compensate for the $O_2$ consumption by humans' activities on land. If fossil fuel combustion is not limited, relying only on the self-adjustment of terrestrial ecosystems will not make much difference in maintaining the atmospheric $O_2$ concentration.

The ocean is the second $O_2$ library except for the continent. Fig. 3a presents the CMIP5 simulated climatological distribution of the oceanic $O_2$ flux, which shows a net influx from oceans to the atmosphere at low latitudes and the opposite occurring at high latitudes, with a global total outgassing of 1.6 Gt per year. The projections of $O_2$ flux under these two scenarios differ in magnitude but follow remarkably similar trends overall (Fig. 3b and c). The global $O_2$ flux will experience increases of 1.2–2.7 Gt/a during the 21st century under RCP4.5 and RCP8.5, respectively, based on CMIP5 models. Although the flux increases under both scenarios, this does not mean that more $O_2$ is produced by marine plants. In fact, the significant decrease in NPP indicates that the ocean $O_2$ production is reduced and the marine environment is experiencing deterioration [22]. Models show that most of the world's oceans are suffering from NPP reduction, including areas where

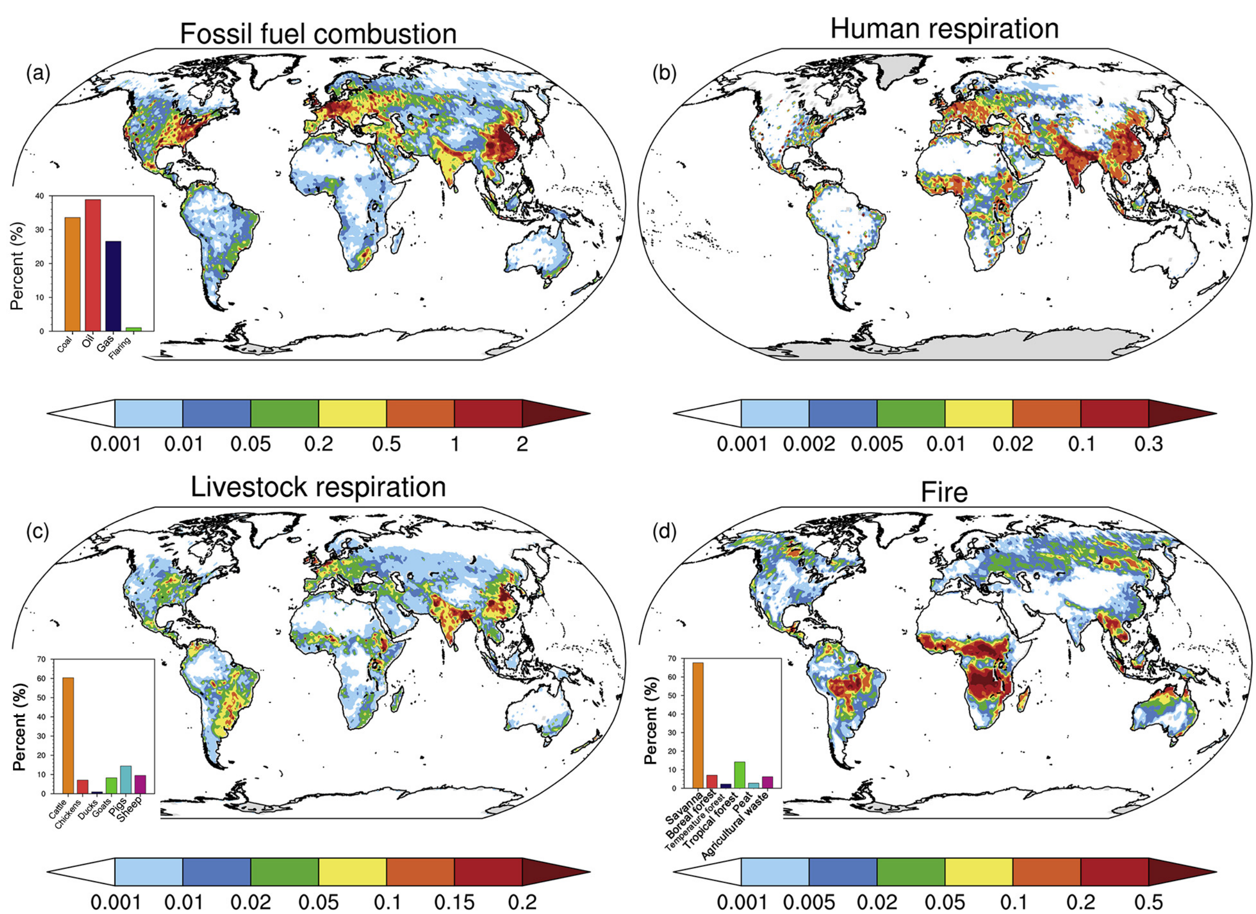


**Fig. 1.** Average global distribution of $O_2$ consumption from 2000 to 2013. (a) Fossil fuel combustion, (b) human respiration, (c) livestock respiration, and (d) fire (including natural and anthropogenic). In the bar plot, the ordinate represents the proportion of oxygen-consuming subtype.

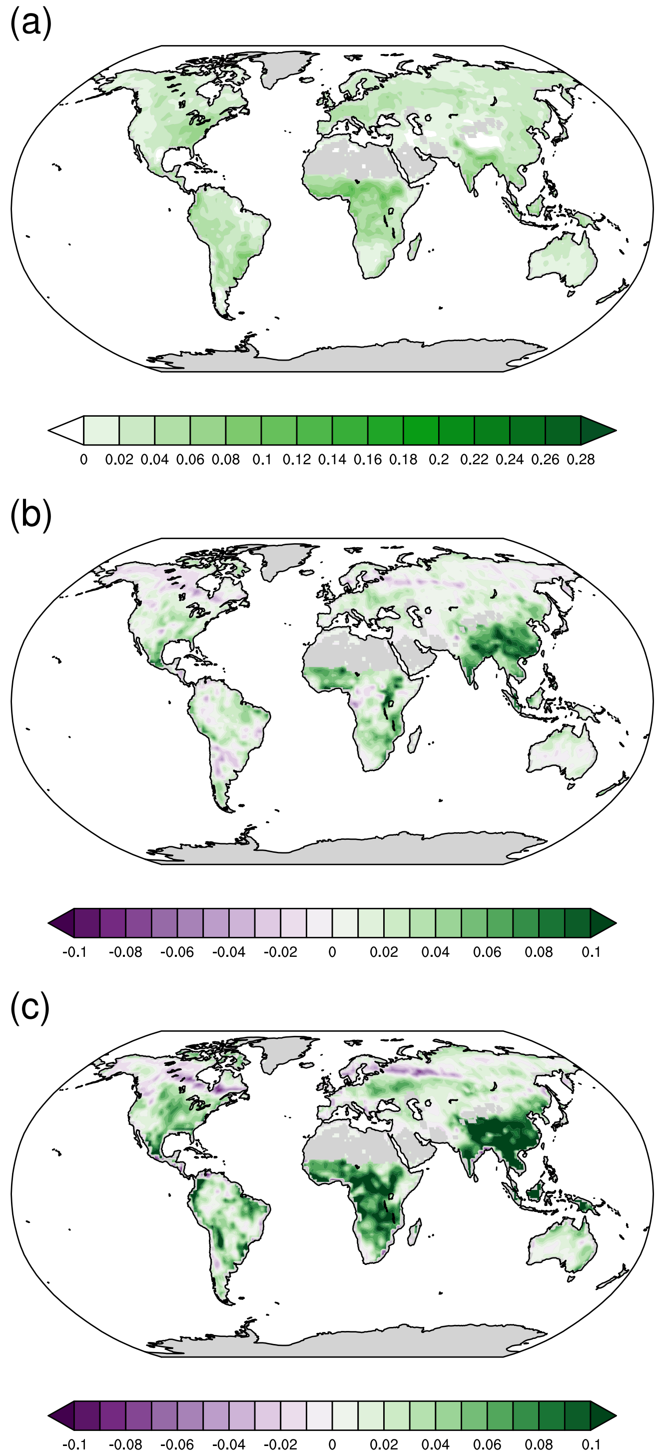


**Fig. 2.** CMIP5 simulated climatological global distribution of NEP and its future changes. (a) The historical climatological global distribution of $O_2$ flux (i.e., average values from 1975 to 2005). The spatial differences between future (i.e., average values from 2069 to 2099) and historical values under the RCP4.5 (b) and RCP8.5 (c). Unit: kg m$^{-2}$ a$^{-1}$.

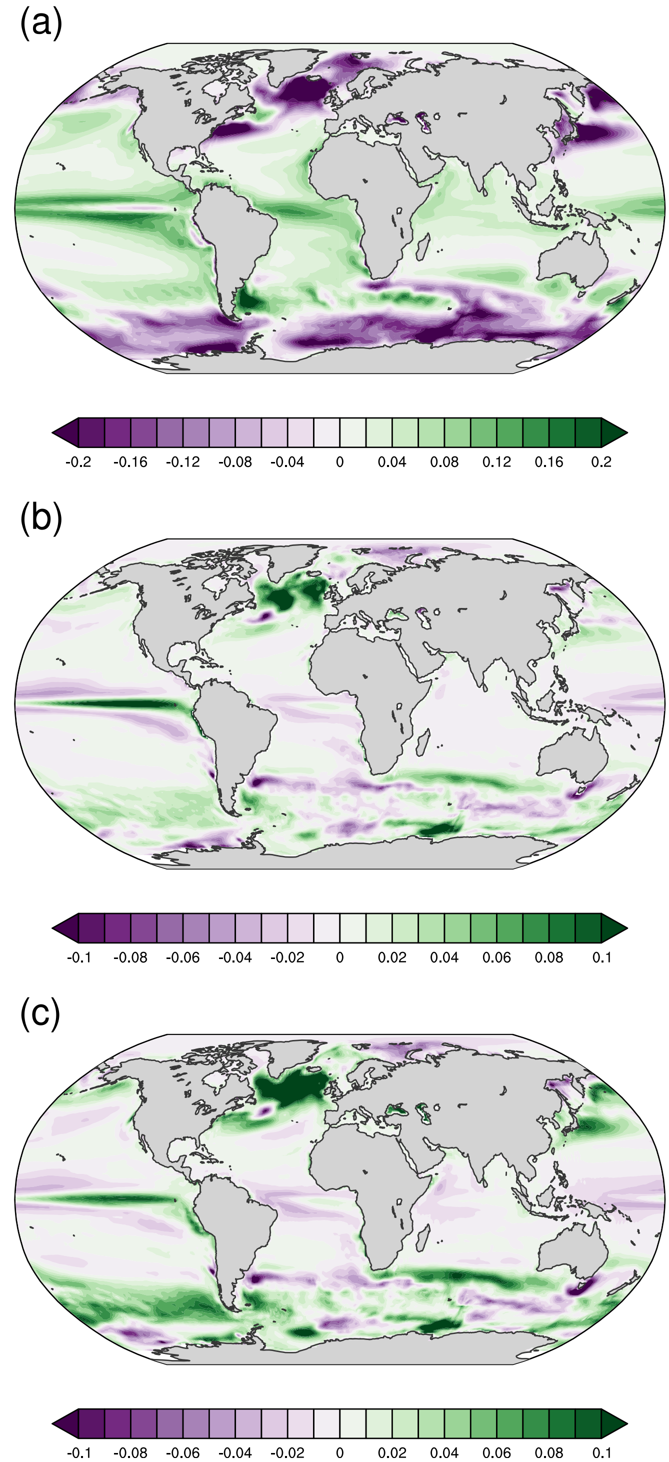


**Fig. 3.** CMIP5 simulated climatological global distribution of $O_2$ flux and its future changes (positive relative to the atmosphere). (a) The historical climatological global distribution of $O_2$ flux (i.e., average values from 1975 to 2005). The spatial differences between future (i.e., average values from 2069 to 2099) and historical values under the RCP4.5 (b) and RCP8.5 (c) scenarios. Unit: kg m$^{-2}$ a$^{-1}$.

oceanic $O_2$ outgassing has increased. The increasing $O_2$ flux may be attributed to the changes of solubility, ocean circulation and convection. An increase in ocean temperature leads to a decrease in solubility and stratifies the ocean, thus limiting ventilation and the supply of $O_2$ to the interior [23–25], causing more $O_2$ to be outgassed from oceans to the atmosphere.

Fig. 4 summarizes the annual averaged global $O_2$ budget from year 1990 to 2005, with the mass of $O_2$ in gigatonnes (Gt) listed in each sink and for each process mentioned above (see Section 2.5). The inputs of $O_2$ to the atmosphere by land and outgassing from oceans are quantified as 16.01 and 1.74 Gt/a, respectively. Fossil fuel combustion, which accounts for the largest consumption of $O_2$ of the three main processes, consumed 25.16 Gt/a. Fire burning consumed 5.87 Gt/a $O_2$. The $O_2$ consumed by human and livestock respiration comprises 3.09 and 2.24 Gt/a,

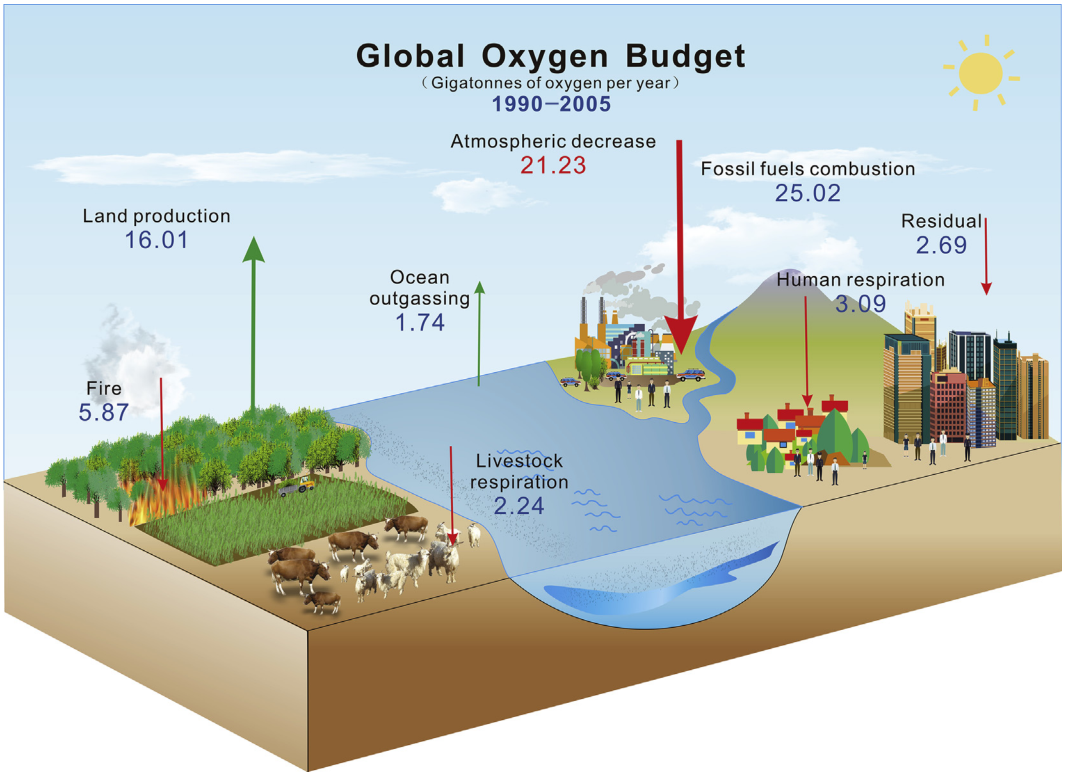


**Fig. 4.** The annual averaged global $O_2$ budget from 1990 to 2005. The green arrows denote the production from land vegetation ($P_{LAND}$) and outgassing from oceans ($O_{OCEAN}$). The red arrows represent consumption by fossil fuel combustion ($C_{FF}$), human and livestock respiration ($C_{RES}$), fire ($C_{FIRE}$) and residual.

respectively. The residual term, which includes the systematic bias, is about 2.69 Gt. In total, the $O_2$ depletion in the atmosphere is 21.23 Gt/a, which is mainly associated with the growth rate of atmospheric $CO_2$ concentration.

Fig. 5a shows the temporal variations of each term of the $O_2$ budget from 1900 to 2100 (with the period of 1990–2005 by historical simulations and 2006–2100 by RCP8.5 projections). The $O_2$ production over land has increased from 5.97 to 17.43 Gt/a, and the fossil fuel combustion has increased from 1.99 to 29.76 Gt/a during 1900–2005. This indicates that the enhancement of photosynthesis rate is not significant compared with the rapidly rising anthropogenic $O_2$ consumption under the background of global warming. The accelerated increasing fossil fuel combustion is the dominant factor which leads to the widening of the gap between $O_2$ consumption and production, and then results in the accelerated depletion of atmospheric $O_2$. By the projections under RCP8.5, this difference between consumption and production would be extended. A significant decrease of $O_2$ appears throughout the whole century, and approximately 100 Gt of $O_2$ would be removed from the atmosphere each year by the end of the 21st century (Fig. 5b). The $O_2$ concentration would decrease from its current level of 20.946% to 20.825% (RCP8.5) and 20.89% (RCP4.5) by the end of the 21st century.

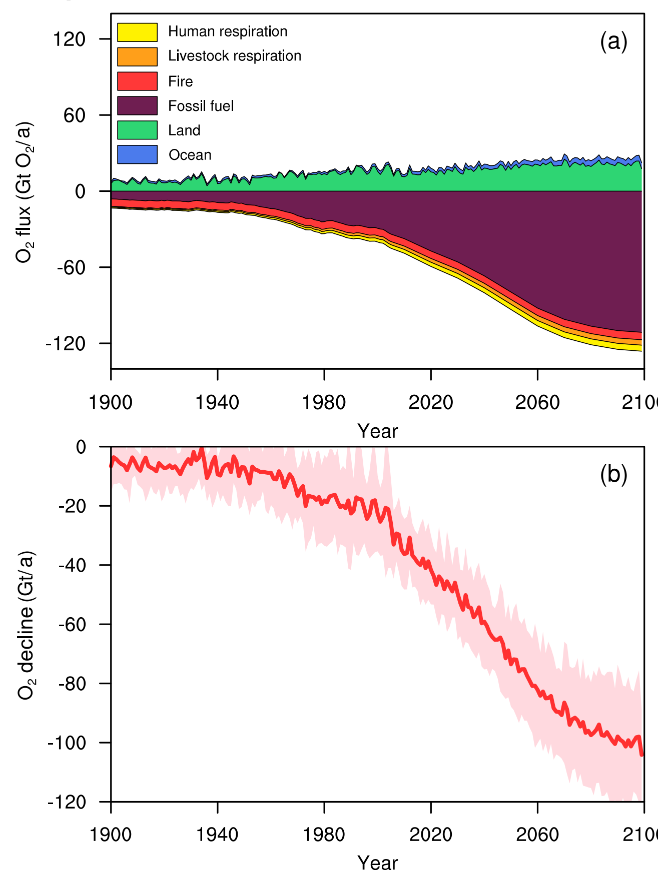


**Fig. 5.** Temporal variation of the global $O_2$ budget from 1900 to 2100. (a) The temporal variation of $O_2$ consumption and producing processes. The shade below zero denotes the processes that remove the $O_2$ from the atmosphere and the shade above denotes the processes that produce $O_2$ to the atmosphere. (b) The temporal variation of annual $O_2$ deficit.

## 4. Conclusion and discussion

The above results indicate that the decreasing trend of atmosphere $O_2$ is significant, which has been much neglected by the public. Here we emphasize that the current $O_2$ that has accumulated in the atmosphere and dissolved in the oceans throughout a billion-year Earth history is not limitless. This $O_2$ inventory is strongly threatened by humans' aggressive activities. Increasing amounts of $O_2$ are being consumed by increasing fossil fuel combustion along with population growth, and accelerated deforestation [26];

moreover, the expansion of drylands [27] will also reduce the $O_2$ production of terrestrial ecosystems. The $O_2$ in the ocean also faces severe threaten. Marine garbage has emerged as a serious problem [28] and the number of dead zones on Earth has doubled every decade since the 1960s [4]; these factors have limited the $O_2$ production in oceans and caused waters to lose $O_2$. The "deoxygenation" and expansion of $O_2$-minimum zones (OMZs) in oceans indicate the arrival of hypoxia in marine ecosystems. These hidden risks associated with the ocean $O_2$ crisis are directly related to the $O_2$ inventory on Earth. All of the cumulative effects described above that limit the output of $O_2$ are putting humanity's future at risk. It is foreseeable that life on Earth will inevitably suffer from hypoxia in the future if we continue these extravagant activities.

Thus, to save our earth, we must take more immediate actions to promote the output of $O_2$ and reduce its consumption, such as by using more green energy instead of combusting more fossil fuels, recycling more municipal and industrial trash on land [29], and using more anaerobic microorganisms to decompose organic matter [30], such that the rate of $O_2$ decline can be decelerated. It is also pivotal to reverse this trend through the combined efforts and cooperation of all countries; otherwise, the human race, as well as other aerobes, will be left behind forever, and our dominance of this planet will become just a brief footnote in its long history [5]. We are entering a new era in Earth's history in which humans, rather than natural forces, are the primary drivers of planetary change. Instead of further degradation, we can redefine our relationship with Earth from a wasteful, unsustainable and predatory one to one where people and nature can coexist in harmony.

## Conflict of interest

The authors declare that they have no conflict of interest.

## Acknowledgments

This work was jointly supported by the National Natural Science Foundation of China (41521004) and the China University Research Talents Recruitment Program (111 project, B13045). The authors acknowledge the Scripps $O_2$ Program of the Scripps Institution of Oceanography for providing atmospheric $O_2$ levels data and the World Climate Recruitment Programme's (WCRP) Working Group on Coupled Modelling (WGCM), the Global Organization for Earth System Science Portals (GO-ESSP) for producing the CMIP5 model simulations and making them available for analysis.

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