

Global warming, human-induced carbon emissions, and their uncertainties

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In recent decades, there have been a number of debates on climate warming and its driving forces. Based on an extensive literature review, we suggest that (1) climate warming occurs with great uncertainty in the magnitude of the temperature increase; (2) both human activities and natural forces contribute to climate change, but their relative contributions are difficult to quantify; and (3) the dominant role of the increase in the atmospheric concentration of greenhouse gases (including CO₂) in the global warming claimed by the Intergovernmental Panel on Climate Change (IPCC) is questioned by the scientific communities because of large uncertainties in the mechanisms of natural factors and anthropogenic activities and in the sources of the increased atmospheric CO₂ concentration. More efforts should be made in order to clarify these uncertainties.

carbon emissions, climate change, global warming, human activities, natural forces, uncertainty

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Global climate change, characterized mainly by global warming, is one of the biggest challenges to human society in the 21st century. Carbon emissions from fossil fuel combustion and land use change are considered the main factors causing global warming [1, 2]. Because carbon emissions affect social and economic development [3–5], climate change has been shifted from an academic topic to an international political, economic, and diplomatic issue.

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988 to evaluate climate changes and their effects on natural and social systems as well as the possible strategies that may be taken by humanity for the adaptation and mitigation of certain issues. The IPCC has published its assessment report every 5 to 7 years since it

published its first report in 1990. Up to now, four assessment reports have been published by the IPCC. In 2007, the fourth assessment report (AR4) was finalized by more than 450 lead authors and over 800 contributing authors from more than 130 countries. The report is considered to reflect the current collective knowledge on the climate system, its evolution, and its anticipated future development [6].

The key points of AR4 are summarized as follows [1]:

(1) The global average temperature has risen by 0.74°C (0.56–0.92°C) in the past century. The rates of temperature increase on terrestrial surfaces are higher than those on oceanic surfaces and increased towards high latitudes in the Northern Hemisphere.

(2) A global average temperature increase is likely because of the increase of greenhouse gas concentrations resulting from human activities such as fossil fuel combustions and deforestation.

(3) The significant global temperature increase will cause

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a series of negative effects on natural systems, including snow and ice melt, sea-level rising, and disturbances in the hydrological cycle; and meanwhile the increase in CO₂ concentrations will lead to the acidification of sea water. Such effects will directly or indirectly threaten terrestrial and marine ecosystems and social systems.

(4) Climate model projections indicate that global surface temperatures are likely to keep increasing by 0.2°C each 10-year in the next two decades. Even if the levels of all greenhouse gas concentrations are stabilized at the levels observed in the year 2000, the global temperature will continue to increase by 0.1°C every 10-year. Global warming will cause further feedbacks by diminishing the absorption capacity of atmospheric CO₂ by land and ocean systems, thereby increasing the proportion of anthropogenic CO₂ emissions that reside in the atmosphere.

For the mechanism of global warming, the IPCC report emphasizes the impact of human activities and the correlation between the CO₂ concentration and temperature increase. However, the Earth is a complex dynamic system with various factors affecting each other; great uncertainties exist regarding causes and effects of the climate changes [7]. Therefore, the claims of the IPCC AR4 have been largely questioned. The Non-governmental International Panel on Climate Change (NIPCC), established in 2007, has introduced a number of controversial and divisive debates [8, 9]. The “Climate-gate” and “Glacier-gate” scandals have especially questioned the public credibility of the report [10, 11]. The IPCC report is no longer the most authoritative document on climate changes, as it is restricted by its political tendencies and some errors and flaws. In response to the sustained criticism and heightened public scrutiny of the IPCC AR4, the United Nations and the IPCC entrusted the InterAcademy Council (IAC) to assemble a committee to independently review the processes and procedures of the IPCC reports. The results of the review indicated that despite the great contributions and successes of the IPCC in general, its fundamental management structure should be reformed and the QA/QC monitoring procedures should be strengthened to process and assess the complex data regarding climate change [12].

At present, the major debates on the claims of the IPCC AR4 have focused on the following four aspects: (1) whether global warming is happening; (2) what are the main driving forces of climate change (i.e. the contribution of human activities and natural processes); (3) whether the future climate change projections based on the existing climate models are accurate; and (4) how about the degree of climate change impact is. Among these debates, the most essential one is whether global warming is caused by human activities or natural processes, which is the fundamental base for the international communities to address climate change and for the negotiation-related carbon emission reduction.

Therefore, correctly understanding climate change issues

and clarifying the focus of debates are the foundation to formulating climate change policies and adapting to and mitigating climate change. We review the occurrence of global warming and its major driving force and discuss the global carbon budget related issues because of their great concern to modern society.

1 Global warming and the related uncertainties

1.1 Evidence for global warming

Whether global warming occurs has been a controversial issue for several years [13, 14], but the standing of such views has changed in recent years [8]. Based on worldwide observations, the global average temperature has risen over the past century [1, 15–18]. This is not only directly observed in the temperature increase, but also is evidenced from indirect observations, such as rising sea levels, melting snow and ice, and changing plant phenology.

(1) Temperature rise. Throughout its long history, the Earth has evolved through glacial and interglacial periods. After the latest glacial period (approximately 12000 years ago), Earth’s temperatures started to continually rise until about 8000 years ago; then it entered cooling period until approximately 300 years ago (around A. D. 1700). Since then, the Earth has entered a warm period, especially in the last century (instrumental observation period), in which the global temperature has increased significantly with increased rates (Figure 1). At present, the Earth is in the warmest period within the past thousand years [1]. In China, temperatures in the last century have also significantly increased at an average rate of approximately 0.5–0.8°C per century. It is especially noteworthy that temperature increased by 0.3°C between the 1980s and 1990s in China [19].

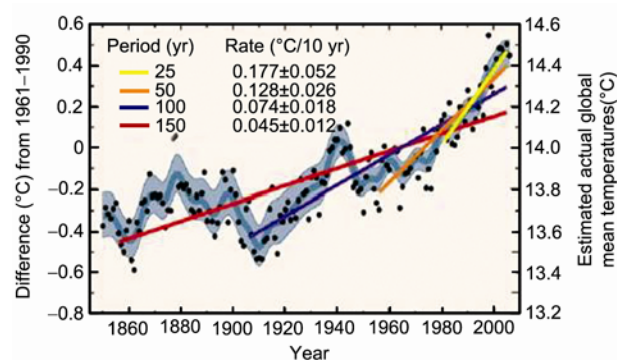


Figure 1 Changes in global average temperature since the modern instrumental observation periods (from 1850) (revised from ref. [1]). The slopes of lines with different color represent the changing rate of different periods: warming at the rate of 0.045°C/10 yr for 1855–2005 (recent 150 years); 0.074°C/10 yr for 1905–2005 (recent 100 years); 0.128°C/10 yr for 1955–2005 (recent 50 years); 0.177°C/10 yr for 1980–2005 (recent 25 years).

There are great regional differences in global warming. In general, the rates of temperature increase on terrestrial surfaces are higher than those on the oceanic surface, and the rates of warming tend to increase towards high latitudes in the Northern Hemisphere [1]. Similar to the globe, in China warming and its rate have also varied in different regions in the past half a century: the temperature increase was first observed in the northeast region in around 1975; then in the eastern and southern coastal regions (1980), in the inland regions (1980), and lastly in the western inland regions (the northwest and the Qinghai-Tibet Plateau) (1983) [20]. The extent of warming was most significant in northeast, northwest and north China and less significant in southwest and south China. This distribution has exhibited great consistency over the last 100-, 50- and 30-year time scales [21].

(2) Sea level increase. Despite the obvious inter-annual fluctuation, the global average sea level has continued to increase since 1870 [1]. From 1961 to 2003, the average rate of sea level increase was 1.8 ± 0.5 mm/yr. This rate has accelerated to approximately 3.1 ± 0.7 mm/yr since the 1990s [1] (Table 1). The sea level increase may be caused jointly by the thermal expansion effect of the oceans warming, glaciers and ice caps melting, and other factors, as shown in Table 1.

(3) Ice melt. Observational data indicate that over the past century, the snow caps have decreased globally. From 1966 to 2005, the satellite-observed snow cap of the North-

ern Hemisphere decreased each month except in November and December. This phenomenon became particularly significant in the 1980s, with a decreasing rate of 5% per year. In the Southern Hemisphere, there has been a decline or no significant change in the snow caps over the past 40 years. The decrease in the snow cap is always attributed to the local temperature conditions. For example, the snow cover in April in the Northern Hemisphere is highly correlated with the temperature in this month at latitudes of 40° – 60° N [1].

The observational data indicate that the decrease in the snow cap also occurred in China between 1960 and 2005, but the overall average snow depth has experienced an increasing trend since 1980s. The changes in the average thickness of snowfall showed a regional variation: decreasing in the South and increasing in the North due to an increase in the northern winter precipitation [22] (Figure 2).

In addition, the global sea ice and glaciers have also exhibited a shrinking trend over the past 150 years. Since 1978, Arctic sea ice has declined at a rate of $2.7\% \pm 0.6\%$ per year, as has the thickness of sea ice [23]. Glaciers and ice sheets have significantly decreased in South American Patagonia, the Himalayas, Alaska, the Northwest United States, and Southwest Canada [24]. However, the Antarctic ice cap is expanding, according to recent reports [25].

(4) Prolongation of the growing season. Phenological observations indicate that the spring phenology of most plants and animals is advancing and the autumn phenology is delayed, resulting in a longer growing season [26–28]. Phenological observations in China show an obvious correlation between phenological inter-annual fluctuations and spring temperature inter-annual fluctuations. The advance in spring phenology is most significant in northeast, north and the Yangtze River areas [29]. Since the 1980s, the spring phenology in Beijing has shown a tendency to increase, especially during 1982–1999. It has advanced by 8.8 days than over the past 140 years [30], whereas the autumn phenology showed an average delay of 0.32 days per year during 1962–2005 [31]. An analysis of the phenology of China's temperate vegetation based on remote sensing data shows

Table 1 Sea level increase rates and contributions of different sources (mm/yr) [1]

Resources	1961–2003	1993–2003
Sea thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35
Combined contribution of individual climate factors	1.1 ± 0.5	2.8 ± 0.7
Observed sea-level increase	1.8 ± 0.5	3.1 ± 0.7

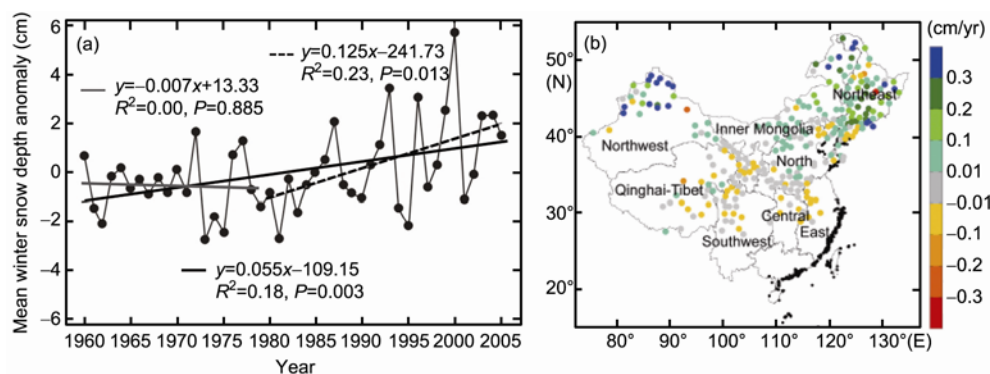


Figure 2 Average depth of winter snowfall in China [22]. (a) Annual change of mean winter snowfall depth; (b) spatial distribution of snowfall depth, showing a decrease in the South and an increase in the North.

that during 1982–1999, the temperate spring phenology advanced on average by 0.79 days, being prolonged by 1.16 days on average [28] (Figure 3). Similarly, using remote sensing data, Zhou et al. [26] suggested that from 1982 to 1999, the vegetation growing season in the Eurasian Continent at north latitude 40°–70° area was prolonged by an average of 18 days, whereas this in the North American continent has prolonged for 12 days.

1.2 Uncertainties in global warming

As stated above, global warming is a basic fact, but there are great uncertainties regarding its magnitude [15, 32, 33]. The main sources of the uncertainties can be summarized as follows:

(1) The temperature profiles of geological history are obtained mainly from proxy data, such as ice cores, ancient pollen, archaeology, tree rings, and ancient literature [34]. The reconstructed paleo-temperature remains uncertain on both local and global scales because the proxy data are limited in their spatial distribution and time span, and some data are not sensitive enough to indicate temperature changes [35]. A single type of proxy data is often insufficient in terms of comprehensiveness and representativeness. Furthermore, different data always show different responses to temperature changes, so the use of different proxy data or

different remodelling methods may provide inconsistent results. Even the same proxy data can produce different results because of complicated relationships among the factors influencing temperature change. For example, tree-ring data, as an ideal proxy indicator, are accurate, and have strong continuity and high resolution, but the relationship between tree-ring and climatic factors is complex, as it is affected not only by temperature but also by CO₂ concentration, precipitation, and other factors.

(2) In the instrumental observation period, the quantity and distribution of meteorological stations have a great influence on the estimates of global temperature: in the early stage there were fewer stations, and they were located mainly in northern middle latitudes, especially in Europe and the United States; then the number of stations increased gradually, but in some regions, especially in the Southern Hemisphere and in marine areas, there were still few or no stations in some areas. This uneven distribution of stations significantly affects the estimation of global temperature and its trend [36].

(3) Over the past century, the worldwide occurrence of urbanization has had profound effects on records of regional and global temperatures because meteorological stations are mostly around urban and suburban areas. For example, annual average temperature, average maximum and minimum temperature, and temperature differences in urban and suburban areas have all increased with the urbanisation and urban area expansion, i.e., by 0.7–1.0°C over the past 30 years (1975–2004) in Shanghai, China [37]. An analysis based on remote sensing and observation data indicates that the urban heat island effect has a great impact on urban and regional temperatures in south China [38]. Similarly, Goodridge [39] found the effect of urban heat islands in America: increasing trend is significant in large cities, less in medium-sized cities, and almost non-existent in small cities.

The contribution of heat islands to regional and global temperature is a controversial issue. The IPCC AR4 (2007) confirmed the effect of heat islands but emphasized that the effect is limited to regional scale, with less than 0.06°C per century for the total global land [1]. Trenberth et al. [40] estimated a contribution to global warming only by 0.02°C per century from 1990. However, what cannot be ignored is that the Earth's surface temperature is calculated by temperature records at meteorological stations, which are always obtained in urban and suburb regions. The calculated values will therefore be affected significantly. For instance, urbanisation contributes to approximately 40 percent of China's warming [41].

(4) Other factors, such as temperature interpolation methods, also affect the estimates of temperature. For example, three temperature series (HadCR UT3, GISS and NCDC) have shown different interpretation values for the temperatures within the past decades. Knight et al. [42] projected a temperature series using HadCR UT3 and re-

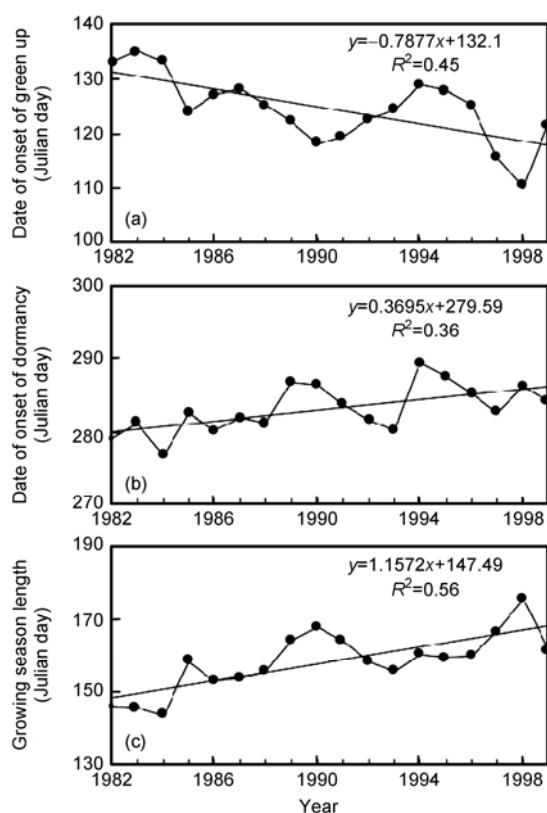


Figure 3 Phenological changes of temperate vegetation in China. (a) Vegetation green returning stage; (b) dormancy stage; (c) length of growing season [28].

vealed that in the past 12 years (1998–2009), the global average temperature did not show a significant change but has been in the high-temperature platform; this observation was also supported by Kerr [43]. However, simulation modelling based on GISS and NCDC temperature series shows that the global temperature in recent decades has had a significant rising [25, 44]. Allison et al. [25] considered that the HadCR UT3 data series did not include information on the Arctic, in which has experienced significant warming in the past 25 years, and hence suggested that the previous projection may have underestimated the warming trend for the past 10 years. A literature-based analysis showed that 1999 to 2008 is still the warmest period over the past 30 years, despite the average temperature not rising in this period. At the same time, the average temperature in China has been rising at a rate of 0.4–0.5°C per ten years, and this trend is especially obvious in northeast China [45]. The debate is still continuing regarding whether the temperature change in the last 10 years has been suspended or is on-going. Hence, observation data covering at least 25–30 years should be collected to illustrate the trend of future climate change and data at 10-year time scale are insufficient for representativeness.

2 Factors affecting climate change and their uncertainties

Multiple factors contribute to climate change, including greenhouse gas concentrations, solar activity, aerosols, deviations in the Earth's orbit, and variations in atmospheric and oceanic circulation. Of these factors, greenhouse gases and aerosol emissions are known to be caused mainly by human activities, whereas factors such as solar activity and volcanic eruptions are regarded as natural factors [1]. According to the IPCC AR4, the current global warming can be ascribed mainly to increasing atmospheric concentrations of greenhouse gases, particularly increasing CO₂ concentrations [1]. Scientists with opposing views claim that natural forces rather than human activity play a larger role in driving climate change, and that the current warming, if examined at the long historical scale, only represents a short stage [8, 46]. The cause of the current climate change, i.e., anthropogenic vs. natural variation, has become a topic of intense scientific debate. The determination of the causes of climate change has a direct and significant impact on global climate negotiations and international policy.

2.1 Contribution of greenhouse gases

Greenhouse gases are gaseous molecules in the Earth's atmosphere that can absorb infrared radiation and can therefore contribute to the atmospheric temperature increase. Without greenhouse gases in the atmosphere, the Earth's surface temperature would be as low as -19°C, which is far

lower than the 14°C that the Earth keeps today. Thus, greenhouse gases have maintained a 33°C increase in the Earth's surface temperature.

The effect of greenhouse gases was first discovered by a French scientist, Joseph Fourier, and subsequently evaluated by a Swedish scientist, Svante Arrhenius, who noted that the Earth's surface temperature would increase by 5–6°C with a doubled CO₂ concentration [47].

The greenhouse gases in the Earth's atmosphere mainly include water vapour (H₂O), CO₂, CH₄, N₂O, tropospheric ozone (O₃), and CFC substances. The warming effect of each type of greenhouse gases is determined by its atmospheric concentration and its warming intensity. Given these two factors, the relative contributions of the Earth's atmospheric constituents to the overall greenhouse gas effect are water vapour (36%–72%), CO₂ (9%–26%), CH₄ (4%–9%), and O₃ (3%–7%) [48].

Greenhouse gases play a crucial role in maintaining a moderate Earth surface temperature that is suitable for survival of plants, animals, and human being. However, the atmospheric concentration of greenhouse gases has significantly increased over the past 150 years due to human activities and this increase is considered the main reason for global warming. During the past 250 years (1750–2008), atmospheric CO₂ concentrations have increased from 280 to 387 ppm, those of CH₄ from 700 to 1745 ppb, and those of N₂O from 270 to 314 ppb, with respective relative increases of 38%, 149% and 16% [1]. The concentration increase of CO₂ is derived mainly from fossil fuel combustion and cement production together with land-use-related emissions (e.g., deforestation in tropical areas). The CH₄ concentration increase is mainly from animal husbandry, paddy fields and wetlands. N₂O mainly arises from agricultural activities such as fertilisation, and CFCs are released mainly from refrigerants used in refrigerators and air-conditioning systems. Only a very small proportion of CO₂ emissions, i.e. approximately 1% of the anthropogenic CO₂ emissions, comes from natural processes such as volcanic activity [49].

Water vapour accounts for 2% of all atmospheric components and is derived mainly from the evaporation of land and ocean surfaces and the transpiration activities of plants. Water vapour contributes the largest greenhouse gas effect and accounts for approximately 1/3–2/3 of the overall effect of all greenhouse gases. The warming effect of water vapour has been ignored for a long time because it was believed that the overall water vapour concentration in the troposphere exhibited no significant changes. Global-warming-enhanced evaporation, therefore, leads to a higher water vapour content within the atmosphere, and more water vapour in turn contributes to greater warming, which is a well known positive feedback mechanism in global warming. This phenomenon is supported by regional observations that during the past few decades, the atmospheric water vapour content has increased in some regions [50–52] (Figure 4).

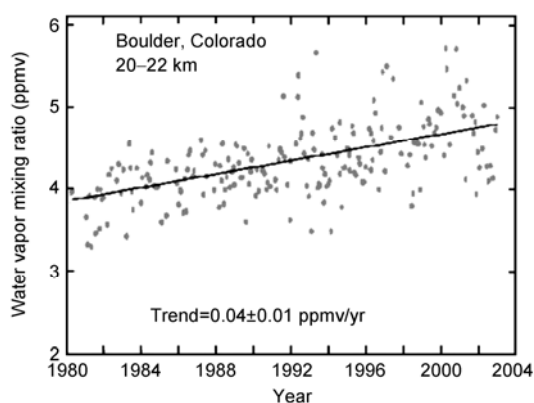


Figure 4 Water vapor content in the stratosphere at Boulder, Colorado, during the past 25 years [50].

2.2 Aerosol effect

Aerosols are fine solid particles suspended in the atmosphere and consist mostly of volcanic ashes, atmospheric pollutants such as SO_2 generated by fossil fuel burning, and particulates arising from biomass burning. Aerosols can affect the near-surface radiation balance and air temperature by affecting atmospheric chemical, radiation and cloud physical processes. Many aerosols, such as sulphate aerosols, biomass particulates, and organic carbons from fossil fuel combustion, exert a cooling influence on climate due to their reflection on the solar radiation. However, some aerosols, such as black carbon suspended in the air from fossil fuel combustion, have a warming effect. There are also aerosols such as mineral dust for which the climate effect is still unclear. In addition to the direct climate effects, aerosols also have a cooling effect through indirect influence on, for example, cloud formation and cloud albedo [53, 54].

The residence time for aerosols is much shorter than that for greenhouse gases, and ranges from hours to days and up to months, but a certain amount of aerosols are always in the atmosphere. Lu et al. [55] showed that the total SO_2 emissions in China increased by 53% from 21.7 to 33.2 Tg during 2000–2006, with a significant regional difference of 85% in the north and 28% in the south. The accurate simulation of aerosol effects on the climate still faces great challenges due to the heterogeneity of aerosol distribution and the complex underlying chemical mechanisms [56]; therefore, great uncertainty still exists with regard to whether aerosols ultimately have a warming or cooling effect [7]. Ramanathan and Carmichael [57] suggested that the emission of black carbon may be the second strongest contributor to the current global warming, second only to CO_2 emissions. The global average of the direct radiative forcing caused by black carbon is up to 0.9 W/m^2 , which is 55% of the CO_2 forcing during the same period. Most studies conclude that aerosols have a cooling effect on climate change but present uncertainties regarding their relative contributions [58–60]. Hansen et al. [59] indicated that the cooling

effect from aerosols can counteract the cumulative global warming from anthropogenic emissions of CO_2 over the past few decades, whereas recent studies suggest that the cooling effect is not strong, i.e. about 10% of the radiative forcing from greenhouse gases [60].

2.3 Influence of solar activity

The Sun is the predominant energy source for the Earth, and solar activity can have a great influence on the variations of Earth's surface temperatures. However, it is difficult to quantify the exact sensitivity of Earth's surface temperature to the solar activity. Some researchers argue that if the solar activity increases, the Earth's surface temperature will rise [61–63]. Observations show that over a long time scale, there has been a good correlation between solar activity intensity and temperature change in northern polar regions [64] and between the variation of average temperature and sunspot activities globally [65]. Most studies support that solar activity was the major factor influencing the Earth's climate before the 1960s, but it seems that the global warming in the recent periods cannot be explained by the solar activity alone [66–68]. Figure 5 shows that the total solar radiation agrees well with the temperature change during 1880–1960, but afterwards, the radiation decreased whereas temperature kept increasing. There are also some studies showing that an increase in solar activity may lead to a temperature decrease. By analyzing the solar radiation spectra data for 2004–2007, Haigh et al. [69] found that the solar activity was much weaker in 2007 than in 2004, but the net energy received at the troposphere was even higher in 2007, indicating that when the solar activity weakens, more visible light arrives at the Earth's surface, thus leading to a temperature increase.

Volcanic activity is another important natural factor influencing climate change. The ashes and gases emitted by a volcanic eruption may have a cooling effect by affecting the atmosphere's transportation and radiation [70, 71]. The influence of volcanic activity on the climate might be de-

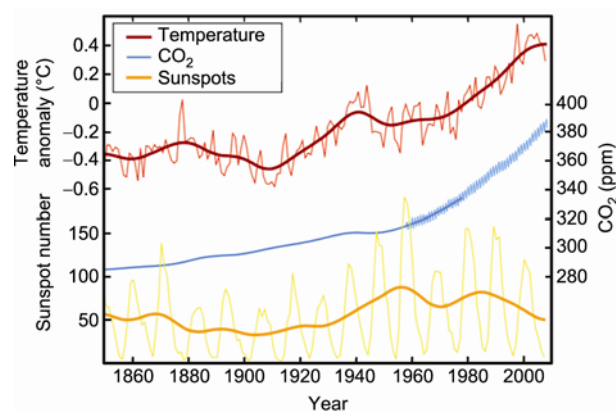


Figure 5 Inter-annual changes of sunspot activities and temperature since 1880 (<http://solar-center.stanford.edu/sun-on-earth/glob-warm.html>).

pendent with the time, location and magnitude of volcanic eruptions and the spatial distribution of volcanic ash [72]. However, it is still difficult to accurately quantify the effect of volcanic activity on the climate because of the lack of a reasonable prediction of volcanic activity and thermohaline circulation change, which might be part of the reason that anthropogenic factors have received a greater emphasis in the current climate warming research [33].

3 CO₂ emissions and global warming

Among the aforementioned greenhouse gases, CFCs, CH₄, and N₂O are less emphasized because the emissions of CFCs have been controlled effectively, and the emissions of CH₄ and N₂O are derived mostly from natural sources. At present, CO₂ is the most attractive anthropogenic greenhouse gas because it is regarded as the major driving force for global warming, and its emission is technically easier to control, compared to other greenhouse gases.

The increase of atmospheric CO₂ concentrations involves several complex processes, such as natural emissions from terrestrial and oceanic ecosystems and anthropogenic emissions from industrial activities, but these processes are unclear. We review the global carbon budget focusing on carbon sources and sinks from the global perspectives of the natural and anthropogenic emissions (Figure 6).

3.1 Global carbon budget and CO₂ in the atmosphere

Figure 6 shows the global carbon budget for 2000–2007. The global terrestrial ecosystem absorbs a total of 120–150

Pg C (1 Pg C = 10¹⁵ g C) annually from the atmosphere (i.e. gross primary productivity, GPP) [75, 76], which should be equivalent to the CO₂ fluxes into the atmosphere arising from plant respiration (autotrophic respiration) and ecosystem heterotrophic respiration (from soil microorganisms and soil animals) in a dynamic equilibrium between the biospheric and atmospheric system.

However, the current global carbon balance is disturbed by two factors: one is anthropogenic carbon emissions from fossil fuel combustion and land use change, which are 9–10 Pg C per year [74], i.e. equal to 1/22–1/26 of the natural emissions from terrestrial and oceanic biospheres; and the other is that increasing temperature can result in a positive feedback of carbon emissions caused from a greater soil heterotrophic respiration and from oceanic ecosystems [77, 78]. This increased emission will be reserved in atmosphere and contribute to the increase of atmospheric CO₂ concentration if it cannot be absorbed by ecosystems. In this sense, in addition to the anthropogenic carbon emissions, the positive feedback of terrestrial and marine ecosystems to global warming may be another important source of the increasing atmospheric CO₂ concentration. The estimation of global carbon budget indicates that a total of the natural and anthropogenic emissions are 250 Pg C per year, whereas the total of absorption by the natural ecosystems and the atmosphere is estimated as 230 Pg C per year (Table 2). This generates a gap of 20 Pg C between the global emissions and absorptions, which is twice the current total anthropogenic emissions (9–10 Pg C/yr). Therefore, there is a great uncertainty in the sources of the increased atmospheric CO₂, and we may not reach to the conclusion that elevating atmospheric CO₂ concentration is mainly from human activities.

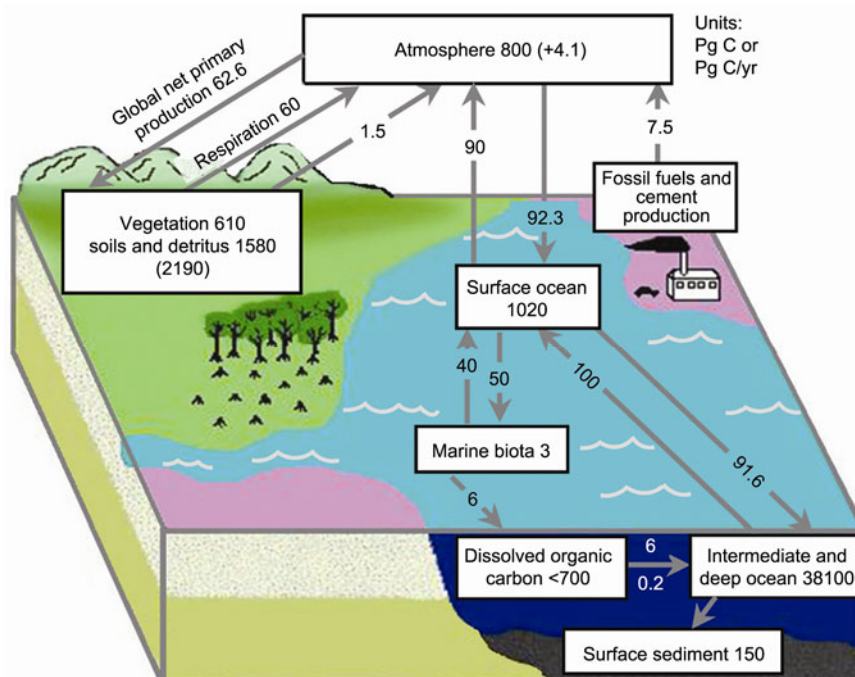


Figure 6 Global carbon budget during 2000–2007. Revised from Schimel [73] and Canadelle et al. [74].

Table 2 Global CO₂ emissions and uptake estimated from refs. [1, 73, 74, 79–84]

Emissions (Pg C/yr)		Uptake (Pg C/yr)	
Natural emissions			
Autotrophic respiration from terrestrial biosphere	60–75	Terrestrial sequestration	120–150
Heterotrophic respiration from terrestrial biosphere	70–100	Ocean sequestration	90–93
Ocean surface emissions	90	Accumulation in atmosphere	4–5
Anthropogenic emissions			
Fossil fuel combustion	7–8		
Deforestation	1.5–2		
Total emissions (mean value)	250	Total uptake (mean value)	230

3.2 Relationship between carbon emissions and temperature increase

The relationship between increasing atmospheric CO₂ concentrations and global warming remains a controversial issue. The IPCC AR4 [1] claims that the observed increase in the global average temperature is very likely due to the increase in greenhouse gas (including CO₂) concentrations. The physical bases for this claim are that: (1) CO₂ is a typical greenhouse gas, and increasing radiative forcing from increasing CO₂ concentrations should result in an increase in atmospheric temperature; and (2) atmospheric CO₂ concentrations have been increasing during the past century, and thus there should be a significant increase of atmospheric temperature. In addition, projections of climate models show that models without anthropogenic forcing cannot reproduce the observed increase in global temperature, even though all of the natural factors and analytical errors are considered. Warming can only be reproduced when both anthropogenic and natural forces are included in the models.

There is great consensus in the scientific community regarding the physical processes of the climate system, but the IPCC AR4 has been challenged for overemphasizing and exaggerating the impact of anthropogenic CO₂ emission and the sensitivity of temperature to atmospheric CO₂ concentrations. However, the relationship between temperature change and increasing atmospheric CO₂ is complicated, making it difficult to accurately assess the sensitivity of the temperature increase to CO₂ concentrations. In this circumstance, radiative forcing is commonly used to quantify the impact of greenhouse gas concentrations on temperature change. Based on multiple studies, the IPCC AR4 (2007) concluded that since the Industrial Revolution, the radiative forcing from increasing atmospheric CO₂ is 1.66 ± 0.17 W/m², and this radiative forcing increased significantly by 20%, especially from 1995 to 2005 [1]. However, recent studies reveal a lower CO₂ radiative forcing [85–87] even when considering different types of research data. Accordingly, the influence of increasing CO₂ concentrations on climate change might not be as significant as the IPCC AR4 reported.

As previously stated, atmospheric temperature is affected by many factors, such as natural processes and aerosols, in addition to greenhouse gases. However, confusion remains

regarding the effect of natural factors on temperature change, especially the effect of aerosols. Global warming hence cannot be fully attributed to the increase of greenhouse gas concentrations. Although there is an obvious positive relationship between temperature change and the atmospheric CO₂ concentration, the determined relationship exists at different scales, such as during the modern instrumental period when negative relationships between CO₂ concentration and temperature were also detected in several periods. In the past 100 years (1910–2010), there was generally a significant correlation between temperature and CO₂ concentration, but the two cooling periods, 1940–1975 and 1998–2009, also saw a significant increase in CO₂ concentrations (Figure 7(a)). We analyzed the relationship between temperature and CO₂ concentration for every 30-year period since 1850 (12 years for the last period). There were three periods with a positive relationship, one with a negative relationship, and two without significant correlations (Table 3). In addition, the relationship between the annual change of CO₂ concentration and temperature was statistically insignificant ($P > 0.05$, Figure 7(b)), even when accounting for the possibility that the temperature change lags behind the CO₂ concentration. All of these findings reveal the complexity of the Earth's climate system, whose mechanisms cannot simply be attributed to a single factor such as CO₂ concentration. Most of the time, a short-term temperature change is influenced more by other factors. For example, Lean and Rind [88] argued that 10-year accumulated cooling effects from natural factors such as solar radiation and volcanic eruptions may cancel out part of the warming effect from greenhouse gases.

In summary, although the increasing CO₂ and other greenhouse gas concentrations were to be considered as the main source of the current global warming [1], there are still numerous challenges and controversies due to the uncertainty and lack of scientific consensus. The projections of future temperatures are continuously increasing, which contrasts with the fact that the average temperatures have fluctuated during the past 150 years. This discrepancy indicates that current climate models do not account for all critical driving factors of temperature change, which can result in considerable uncertainties in their projections [89]. Therefore, the emission reduction targets are doubtful aiming to prevent global temperatures from rising more than 2°C (re-

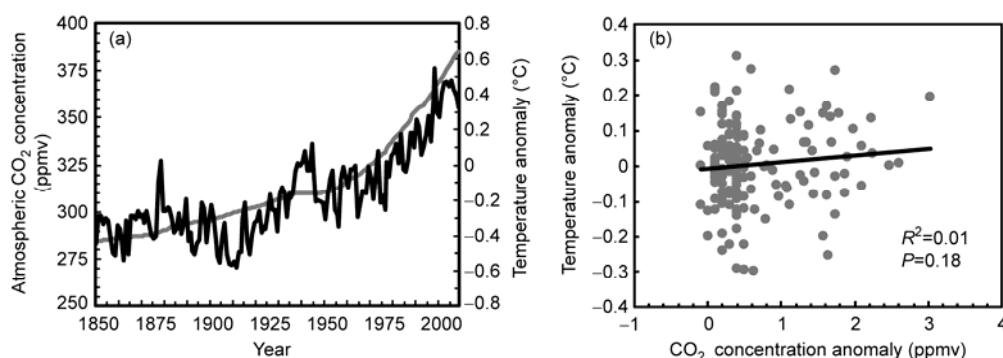


Figure 7 Relationship between atmospheric CO₂ concentration and global mean temperature. (a) Changes in atmospheric CO₂ and global mean temperature; (b) relationship between annual increment in CO₂ concentration and global mean annual temperature.

Table 3 Correlation coefficients of atmospheric CO₂ concentrations and global mean temperature every 30-year since 1850^{a)}

Period	Initial sequence coefficient
1850–1880	0.46 [*]
1881–1910	-0.61 [*]
1911–1940	0.84 [*]
1941–1970	0.02
1971–1997	0.79 [*]
1998–2008	-0.02

a) * $P < 0.05$.

sponding to 450–550 ppmv of CO₂ concentrations in atmosphere) based on the IPCC AR4 [85, 90, 91]. An objective, acceptable viewpoint should be that, as a major greenhouse gas, an increase in the CO₂ concentration should have contributed to global warming, but the magnitude of this increase is an open question. Therefore, greater efforts should be directed towards a better understanding of the underlying mechanisms of warming in both anthropogenic and natural dimensions as well as the determination of the source of the increased CO₂ concentration in the atmosphere before solid conclusions are reached and policy decisions made.

4 Conclusions

(1) Global warming is an objective fact with great uncertainty in the magnitude of the temperature increase. Worldwide observational data indicate that the global average temperature has increased during the last century. In addition to rising temperatures, evidence of global warming also includes the global increase in the average sea level, widespread snow and ice melt, and changes in plant phenology. However, this still has large uncertainties in the magnitude of the global temperature rise.

(2) Both human activities and natural factors contribute to climate change, but it is difficult to quantify their relative contributions. Both anthropogenic and natural factors influence the global climate system. Human activities, espe-

cially fossil fuel combustions and deforestation, cause emissions of greenhouse gases such as CO₂ and CH₄ as well as aerosols such as SO₂, whereas natural factors such as solar activity and volcanic eruptions generate an alteration of solar radiation, atmospheric and oceanic circulations, and atmospheric components. In general, greenhouse gases have warming effects, whereas aerosols lead to cooling. Water vapour is the greatest contributor to the greenhouse gas effect. Although its concentration in the troposphere exhibits no significant changes over the last decades, there is an obvious parallel oscillation between the warming effect of water vapour and the greenhouse gas concentrations. The impacts of natural and anthropogenic factors, especially the aerosols, are uncertain.

(3) The IPCC claimed that the increase in atmospheric concentrations of greenhouse gases (including CO₂) is the driving force for climate warming, but this has been questioned by the scientific community. Based on the physical foundation of the greenhouse effect and projections of climate models, the IPCC AR4 (2007) concludes that global warming is very likely caused by the increase in CO₂ and other greenhouse gas concentrations. This conclusion has generated considerable controversy, and the debates have focused on the following four points: 1) it remains unclear how the human and natural factors, especially the aerosols, affect the global temperature change; 2) over the past century, the temperature change has not always been consistent with the change of CO₂ concentration. For several periods, global temperatures decreased or were stable while the atmospheric CO₂ concentration continuously increased; 3) there is no significant correlation between the annual increment of the atmospheric CO₂ concentration and the annual anomaly of annual mean temperature; and 4) the observed significant increase of the atmospheric CO₂ concentration may not be totally attributable to anthropogenic emissions because there are great uncertainties in the sources of CO₂ concentration in atmosphere.

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