perature of ~15 °C (~288 K). Notably without any greenhouse gases in the atmosphere, Earth's temperature would be 255 K (*i.e.*, atmospheric effective emissivity of 0).

Both solar radiation and emitted energy from Earth are transported through photons. These photons travel at the speed of light ($c = 3 \times 10^{10}$ m s^{-1}) and behave as particles and waves. The spectral density of radiation by wavelength under a thermal equilibrium at a given temperature (T) is calculated as:

$$E = \frac{h \cdot c}{\lambda} \tag{5.2}$$

where h is Planck's constant (6.6256×10^{-34} J s), and λ is the wavelength of the photons (μm). Planck's law also defines the radiant spectral flux density as:

$$E(\lambda, T) = \frac{2 \cdot \pi \cdot h \cdot c^2}{\lambda^5 \cdot \left(e^{\frac{h \cdot c}{\sigma \cdot \lambda \cdot T}} - 1\right)} \tag{5.3}$$

Equations (5.2) and (5.3) define the radiant emittance from the Earth. Based on Planck's law, radiant emittance from the sun ($T = 6000$ K) varies from 0.2 nm to 3.0 nm and peaks at spectra of ~0.55 nm, with most energy coming from a wavelength of 0.3–0.7 μm (>50%). These wavelengths are loosely called "shortwave radiation" or "visible light". The Earth's ($T = 288$ K) peak emittance is 9.5–10.0 nm. In sum, Earth's temperature is mostly maintained by the balance of incoming shortwave radiation from the sun and outgoing longwave radiation from the Earth.

5.1.2 The Greenhouse Effects

This energy balance is maintained by assuming that three major components of the Earth system remain the same: water (oceans and inland lakes), land surface, and the atmosphere. While the division between land and water has been stable since the last glaciation, atmospheric composition and land surface properties have gone through rapid and magnificent changes, mostly due to increasing use of fossil fuels and land conversions. Excessive consumption of fossil fuels (*e.g.*, coals, crude oil, natural gases, *etc.*) has been substantially changing atmospheric composition, which in turn alters both incoming shortwave and outgoing longwave radiation. Due to extensive and intensive land use, terrestrial ecosystems have very different capacity for converting atmospheric CO_2 to biomass through plant photosynthesis (Chapter 2), uptaking CH_4 into soils through methane oxidation, producing CH_4 in the soil, decomposing dead organic materials for respiring (Chapter 3), partitioning latent and sensible heat differently (Chapters 1 and 4), releasing more N_2O due to elevated fertilization, and others. All of these changes in ecosystem structure and functions have direct consequences on many chemical species of the atmosphere. As illustrated in Figure 5.1a, the CO_2 concentration of the atmosphere increased from 337 ppm in 1979 to 407 ppm in 2018. Similarly, N_2O and CH_4 concentrations that were 301 ppb and 1578 ppb, respectively, in 1979 rose to 331 ppb and 1858 ppb, respectively, in 2018. The decadal increase in CO_2, N_2O and CH_4, on average, was 17.6 ppm, 7.5 ppb, 59.2 ppb, respectively, during this 40-year period. As a result, the radiative forcing (RF) due to these increasing concentrations has been elevated, with a higher increasing rate for CO_2 and N_2O than CH_4 (Fig. 5.1b). When examined for their relative importance of the total, CO_2 increased from 66.8% to 74.2%, CH_4 decreased from 26.4% to 18.6%, and N_2O increased from 6.8% to 7.2% (Fig. 5.1c). These changes in their importance in contributing the warming trend highlight the recent increasing interest in N_2O.

Earth's atmosphere is composed of many gases and particles. Nitrogen (~78%) and oxygen (~21%) are the two major chemical species. Other species, including water, argon, carbon dioxide, neon, helium, methane, krypton, hydrogen, nitrous oxide, xenon, ozone, carbon monoxide, and ammonia, account for $<1\%$. The atmosphere also contains a large amount of particulate matters and biological materials that can affect the energy balance of the Earth. For example, an increase in the amount of aerosol deposition on snow and glacier surfaces will reduce reflection (*i.e.*, lowered albedo) and, consequently, keep more energy within the Earth system. Volcanic eruptions, large-scale fires, and industrial production are major sources of aerosols at global scale.

If these gases and particular matters had the same reflection (or scattering) and absorption to radiation at all wavelengths, the energy balance of the Earth would not be affected. Unfortunately, this is not the case (Fig. 5.2). Ozone (O_3) absorbs almost all wavelengths of <300 nm (*i.e.*, ultraviolet radiation, UV), and water (H_2O) absorbs many wavelengths of >700 nm. This suggests that a reduction in ozone concentration would increase the amount of incoming UV light on the Earth's surface. This process witnessed rapid change during a period of increased chlorofluorocarbon emissions from a variety of industrial processes until their ban in the late 1980s that reduced ozone concentration in the stratosphere. Water vapor emissions from high-altitude flight also contribute to this ozone depletion, but this is

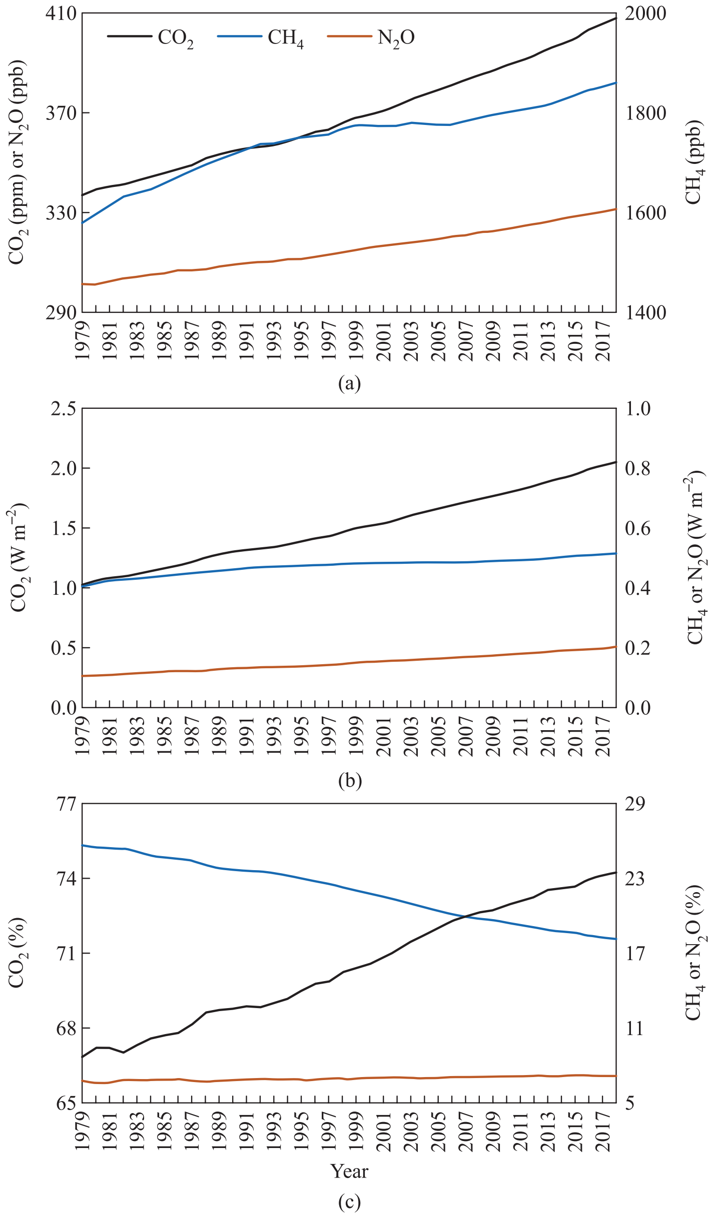

Fig. 5.1 Long-term changes in three major greenhouse gas (GHG) species (CO_2, CH_4 and N_2O) (a) concentrations, (b)their radiative forcing (RF), and (c) their RF portion of the total during 1979–2018 [1].

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1 Data source: https://www.esrl.noaa.gov/gmd/aggi/NOAA_MoleFractions_2019.csv(downloaded on 29 March 2020).

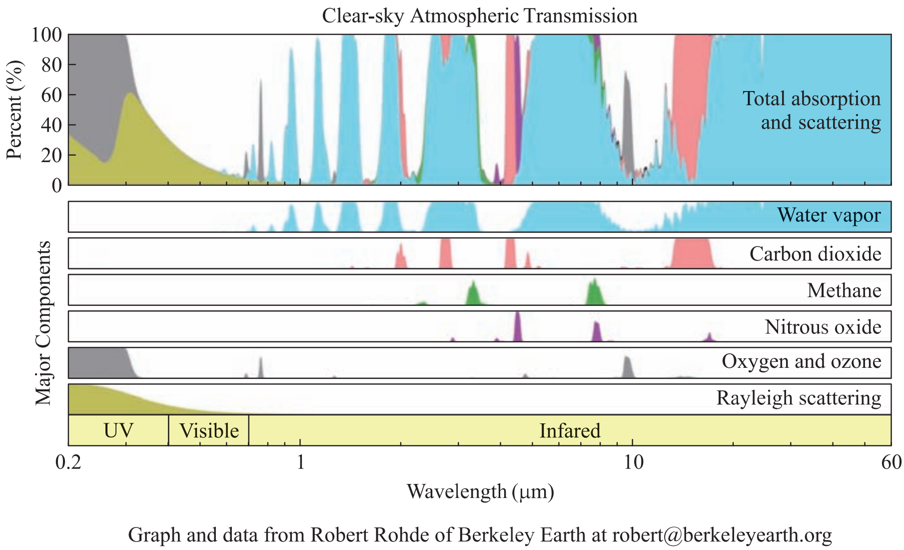

Fig. 5.2 Spectral distribution of solar radiation intensity and absorptions by water vapor and major greenhouse gases. Absorptions were computed using the HiTRAN database[1], and the US Standard Atmosphere with the assistance of Brad Schrag's PyRad analysis package by Robert Rhode of Berkeley Earth (permission received on April 3, 2020).

a much smaller cause of ozone loss than CFCs. Fortunately, according to Planck's law (Eq. 5.3), the total amount of energy from UV radiation is small because of the shorter wavelength. Meanwhile, water vapor can absorb a large amount of longwave radiation in a large number of wavelengths, and thus is the primary greenhouse gas on Earth, resulting in a planet that maintains a temperature that supports life. Liquid and frozen water behaves similarly. This is the reason cloudy nights are typically warmer than clear nights. Fortunately, water vapor has a short lifespan (*e.g.*, hours to days) in the atmosphere and its quantity in the atmosphere is determined by evaporation and condensation processes that are functions of temperature. Humans cannot significantly modify water vapor concentration. Rather, water vapor changes as temperature changes due to changes in greenhouse gases like CO_2. Thus the climate effect of change in water vapor is called a climate feedback. Roughly, the relative humidity of Earth has stayed constant.

Unlike H_2O, there are serious concerns about trace gases that humans can modify directly by emissions. As shown in Figure 5.2, GHGs such as CH_4, N_2O, O_2, and O_3 can absorb radiation at several wavelengths, with

[1] https://hitran.org/data-index/

CO_2, CH_4 and N_2O representing the top three species in terms of absorption of longwave radiation. The abovementioned mechanism for keeping energy within a system is illustrated in pioneering experiments by John Tyndall and Joseph Fourier, whose work in the mid-1800s found that glass lets most shortwave radiation through, while it intercepts most longwave radiation — known as the "greenhouse effect". This principle is widely used to grow vegetables and crops in glass greenhouses because a greenhouse reduces turbulent mixing while allowing for solar absorption that leads to a higher temperature. In the case of the Earth system, the atmosphere functions similarly to glass. In 1896, Swedish scholar Svante Arrhenius concluded that fossil fuel combustion may eventually result in enhanced global warming. He predicted that a doubling of CO_2 concentration would lead to a 5 °C increase in global temperature. His warning was mostly ignored until the late 1950s. Roger R. D. Revelle and other pioneering scholars started scientific investigations on anthropogenic influences on global warming (*see* more detailed history in Archer and Pierrehumbert 2011). However, they hypothesized that oceans would absorb all the CO_2. Through the establishment of the International Geophysical Year (IGY) in 1958, the Atmospheric Carbon Dioxide Program was promoted to instrument two monitoring stations the Mauna Loa Observatory on Mauna Loa, Hawaii, and in Antarctica, with Charlie D. Keeling as the lead investigator. Later, the change in atmospheric CO_2 concentration became known as "the Keeling Curve" — a measure that is widely used in many current studies in global climate change and ecosystem science.

In 1967 Manabe and Wetherald (1967) published a groundbreaking paper based on the first generation of computer modeling. They stated that "The results show that it takes almost twice as long to reach the state of radiative convective equilibrium for the atmosphere with a given distribution of relative humidity than for the atmosphere with a given distribution of absolute humidity. Also, the surface equilibrium temperature of the former is almost twice as sensitive to change of various factors such as solar constant, CO_2 content, O_3 content, and cloudiness, as that of the latter, due to the adjustment of water vapor content to the temperature variation of the atmosphere." They concluded that "A doubling of the CO_2 content in the atmosphere has the effect of raising the temperature of the atmosphere (whose relative humidity is fixed) by about 2 °C." This early report set the stage for future investigations on the influences of CO_2 to global climatic change. In the late 1980s the scientific community realized the escalating increase in CO_2 concentration changed interdependently changes with global temperature. In 1988 the Intergovernmental Panel on Climate Change (IPCC) was founded by the United Nations Environmental Program (UNEP) and the

World Meteorological Organization (WMO) to assess the warming trend, explore the underline mechanisms, and predict future temperature under various scenarios. Quantifying the contributions of various greenhouse gases for their GWP has been the major task of the IPCC and the scientific community since then. For IPCC working groups, climate forcing is defined as "An externally imposed perturbation in the radiative energy budget of the Earth climate system, such as through changes in solar radiation, changes in the Earth albedo, or changes in atmospheric gases and aerosol particles." Climate forcing is the changes that can make current climate different.

In sum, greenhouse gases (GHGs) warm the Earth by absorbing energy and slowing the rate at which that energy escapes to outer space; they act like a blanket insulating the Earth. Different GHGs can have different effects on the Earth's warming (Fig. 5.2). Two key measures for assessing their effects are concentration, which determines the radiative efficiency of a GHG species, and lifespan (*i.e.*, how long it stays in the atmosphere). The contribution of each GHG species is quantified by calculating its GWP by converting its impact on CO_2 equivalence (*i.e.*, CO_2-equivalent) over a certain time horizon (TH) (*i.e.*, 20, 50, 100, 500 years, as applied in the IPCC reports). CO_2 has a lifespan of approximately 120 years, but it varies between 5 years and 200 years because its sources and sinks operate on many timescales while atmospheric sink is very small in the atmosphere; whereas CH_4 and N_2O have estimated lifespans of 12.4 and 120 years, respectively. In the literature, the term global warming impact (GWI) generally is used interchangeably with the more commonly used GWP.

5.1.3 The Roles of Terrestrial Ecosystems in GWP

Terrestrial ecosystems were hypothesized to play an important role in regulating the amount and dynamics of GHG (including water) as well as albedo. In the 1990s, after the First Assessment Report (FAR) of the IPCC (Houghton and Giddes 1992), a major hypothesis was that the "missing carbon" or unaccounted mismatch between accelerating fossil fuel emissions and the slower than expected growth rate of atmospheric CO_2 in the global carbon budget might be due to a significant underestimation of terrestrial carbon sink strength through photosynthesis (Sundquist 1993). Substantial research since 1990 has been conducted to quantify the carbon sequestration strength of global ecosystems. A parallel effort was made to quantify the amount of contributions from various GHGs (Lashof and Ahuja 1990, Rodhe