The present work was submitted to the Faculty of Engineering

Long-term trends of greenhouse gases in an arid and semi-arid area of Mongolia and its relationship with temperature

Bachelor Thesis

by

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Ulaanbaatar, 05/15/2022

Statutory Declaration

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Abstract

Over the past few decades, the Earth's climate has been dramatically changing due to anthropogenically-induced greenhouse gases. CO_2, CH_4, N_2O, and SF_6 concentrations have been continuously increasing. In this study, 29-year measurement data was used to conduct basic research covering several aspects including general characteristics of greenhouse gases, their climate radiative forcing, and relevance to temperature. A particular investigation was done on a variety of analyzes such as time series, seasonal changes, future forecasts, and temperature correlation. Using the statistical model, By 2033, the concentrations of greenhouse gases in Mongolia are predicted to increase by 3-12.1% compared to the current level. In Mongolia, 73.4% of the climate radiative forcing is CO_2, 19.6% is CH_4, 6.64% is N_2O, and 0.35% is SF_6. Furthermore, the relationship between greenhouse gas and temperature showed that CO_2 and CH_4 have the highest correlation (0.42 and 0.41) during the study period.

Keywords: greenhouse gas, climate change, global warming, radiative forcing, Mongolia

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List of Abbreviations

GHG	Greenhouse gas
NOAA	National Oceanic and Atmospheric Administration
GML	Global Monitoring Laboratory
IRIMHE	Information and Research Institute for Meteorology, Hydrology and Environment
AR	Assessment Reports
ALT	Alert, Nunavut, Canada
MLO	Mauna Loa, Hawaii, United States
WLG	Mt. Waliguan in China
SYO	Syowa Station, Antarctica
TAP	Tae-Ahn Peninsula, Korea
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
UUM	Ulaan-Uul, Mongolia
UNEP	United Nations Environment Programme

1. Introduction

1.1 Background

Changes to environmental components such as biosphere, ecosystems, atmosphere, hydrosphere, natural resources, etc. are affected directly or indirectly by humans and are referred to as human (or anthropogenic) effects on the environment. Sudden global warming, environmental degradation (such as ocean acidification), mass extinction and biodiversity loss, ecological crises, and ecological collapse occurring during the last decades are all consequences of changes in the environment due to human activities. Population expansion, overconsumption, overexploitation, pollution, and deforestation are some of the human activities that harm the environment on a global scale (either directly or indirectly). Some of the issues, such as global warming and biodiversity loss, have been described as posing catastrophic hazards to the human species' survival [1].

The Earth's atmosphere consists of 78 percent of nitrogen, 21 percent of oxygen, and 1 percent of argon gas. The rest 1 percent constitutes of “greenhouse” gases (GHGs). There is a term called "greenhouse effect", which is now often used to indicate an increase in the temperature of the lower atmosphere as a consequence of the human-induced release of carbon dioxide (CO_2) and other trace gases into the atmosphere. However, the GHGs are small in terms of amount, but they play a key role in Earth’s heat budget maintaining the balance of atmospheric radiation and chemical conversion. GHGs include water vapor, CO_2, methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). According to Kondratyev (1988), CO_2 provides roughly 21.7%, CH_4 2.4%, N_2O 4.2%, and 2.4% of other gases to the atmosphere's mean "greenhouse effect" [2].

One of the biggest evidences of the GHG effect is temperature rise in the Earth’s lower layer of atmosphere. In terms of global warming, there are significant geographical disparities. It is indicated that doubling atmospheric CO_2 would result in a 1.2°C increase in the surface and tropospheric temperature [3]. Also, CO_2’s radiative forcing would grow by around 4 W/m2 if it was doubled. As reported by several estimates, 4 W/m^2 generated by a doubling of CO_2 in the atmosphere could result in global warming of 3.5 to 5°C and due to climate change, the sea level has been increasing. Despite clear inter-annual variations, the worldwide average sea level has been rising since 1870. From 1961 to 2003, the average annual increase in sea level was 1.8±0.5 mm. Since 1990, this pace has increased to roughly 3.1±0.7 mm/yr. [4]. The thermal expansion impact of warming oceans, melting glaciers and ice caps, and other reasons may all contribute to rising sea levels. Besides those effects, there is a lot of other evidence such as drought, desertification, precipitation, heavy rainfall, flood, and typhoons.

Mongolia is particularly vulnerable to a shift in geo-climate zones caused by climate change due to its location in the transition zone between the Siberian taiga and the Central Asian desert. As for Mongolia, temperatures increased by 2.24°C on average between 1940 and 2015 [5]. This increase has been linked to a decrease in frost days and an increase in hot summer days, as expected. The rate of temperature rise varies differently; over the same period, maximum temperatures have risen by 2.6°C while minimum temperatures have only risen by 0.3°C [6]. In Mongolia, poor climatic conditions have already created one of the most formidable impediments to economic development, and climate change is expected to exacerbate this. Mongolia's ecosystems have changed as a result of climate change and human activity over the last 40 years. Desertification, soil erosion, and deterioration of water resources and biodiversity are only a few of the changes that have occurred.

To combat and reduce these problems, The Intergovernmental Panel on Climate Change (IPCC) publishes comprehensive Assessment Reports (AR) on the status of scientific, technical, and socioeconomic knowledge regarding climate change, its impacts, and future hazards, as well as solutions for slowing down the rate of change. According to their predictions, limiting global warming to 1.5°C would necessitate a peak in greenhouse gas emissions by 2025 at the latest, and a 43% reduction in emissions by 2030; at the same time, methane emissions would have to be lowered by nearly a third. Even if they succeed, it is nearly certain that they will momentarily exceed this temperature threshold, but that they will return to it before the end of the century. When carbon dioxide emissions are reduced to zero, the global temperature will settle. This entails achieving net-zero carbon dioxide emissions globally in the early 2050s for 1.5°C and the early 2070s for 2°C. This analysis demonstrates that keeping global warming below 2°C still necessitates a peak in global greenhouse gas emissions by 2025 at the very latest, and a quarter reduction by 2030 [7].

1.2 Objective of the study

Based on the current knowledge and other necessities in science and practice, the current study aims to achieve the following goals through conducting basic research:

1. Study and review the processes that lead to the increase in GHGs and their effects
    - Sources of GHGs, its historical overview, recent changes
    - GHG effect, its impact on the global atmosphere
    - Overview of global warming in arid and semi-arid areas
    - Climate change in Mongolia
2. Investigate the characteristics of GHGs and warming in an arid and semi-arid area
    - Analyze characteristics of GHGs at Ulaan-Uul, Dornogovi, station over a long term
    - Compare the GHG trends with sites in other parts of the world and East Asia
    - Investigate the relationship between GHG concentrations and mean temperature change
3. Predict the future changes in GHGs

- Predict possible future changes in GHGs at Ulaan-Uul station based on historical data
- Predict the warming at Ulaan-Uul station until 2033

4. Discuss the findings

- Compare findings of this study with other studies
- Compare the characteristics of the GHGs with those in other parts of the world
- Suggest further detailed research directions.

2. State of the Art

2.1. Greenhouse gases

The temperature of the Earth's surface is controlled by the major source of energy in our solar system – the Sun. The shortwave radiation from the Sun is absorbed by the Earth's surface and converted into long-wavelength thermal radiation when it is radiated from the surface back to space. Some of the gases in the atmosphere absorb this long-wave radiation and radiate it back to the Earth's surface, causing additional warming in the lower atmosphere, a phenomenon known as GHG (Figure 1). Without these gases, the world would be so much higher than today's temperature. Thus, having a proper level of GHG is not harmful or dangerous to the world. However, because of human activity primarily, over the last 150 years, the world's GHG has increased and has already passed the safe level for the atmosphere. Humans currently emit 9.5 billion metric tons of carbon into the atmosphere each year by burning fossil fuels, with another 1.5 billion metric tons emitted from deforestation and other land cover changes. Forests and other vegetation take roughly 3.2 billion metric tons of human-produced carbon per year, whereas the ocean absorbs about 2.5 billion metric tons. Every year, a net 5 billion metric tons of human-produced carbon is released into the atmosphere, increasing global average carbon dioxide concentrations by around 2.3 parts per million [8].

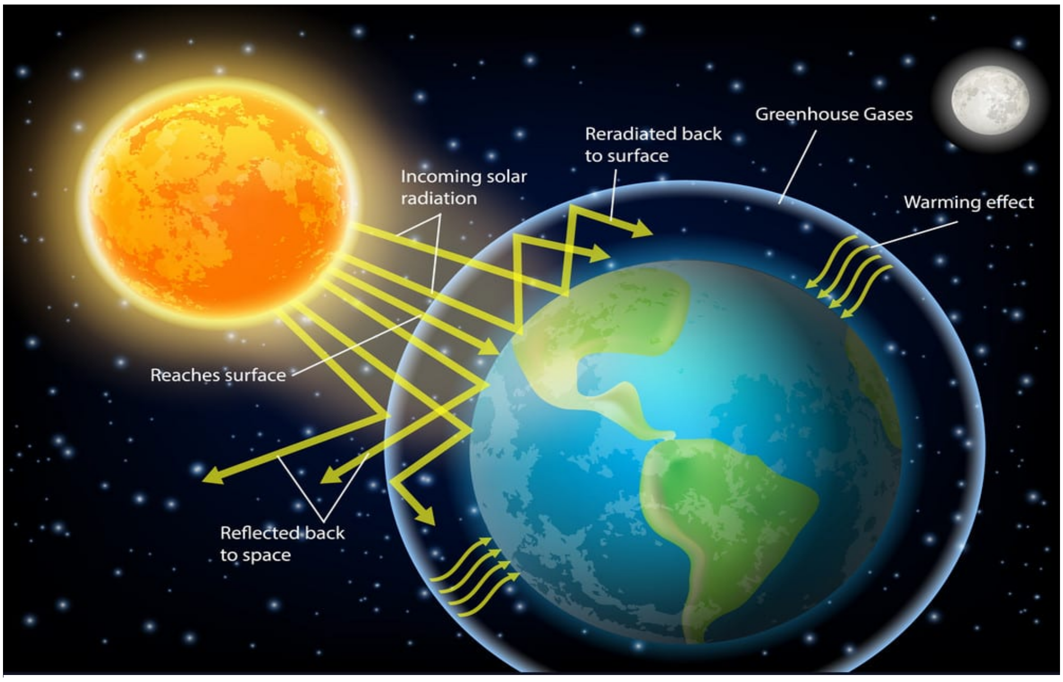

Figure 1. Greenhouse gas effect

There are significant gases that result from human activities and are responsible for the GHG effect:

- Carbon dioxide (CO_2) - Carbon dioxide is a colorless, non-combustible gas at normal temperatures and pressures. Even though it occurs naturally in Earth's carbon cycle such as soil, plants, and animals' carbon cycle, it is increased by human activities. Examples: burning fossil fuels for heat and electricity and deforestation. Over the last 41 years, CO_2 levels in the atmosphere have increased by an average of 1.85 parts per million (ppm) every year (1979-2020). CO_2 levels are rising faster than ever before; after averaging around 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the rate has accelerated to 2.4 ppm per year in the recent decade (2009-2020). The yearly CO_2 increase from 1 January 2020 to 1 January 2021 was 2.50±0.08 ppm, which is slightly more than the preceding decade's average and significantly greater than the prior two decades [9].
- Methane (CH_4) - Methane is a colorless, odorless gas found in abundance in nature and a byproduct of certain human operations. Leaks from natural gas systems and livestock husbandry are two examples of human activities that emit methane. Methane has a far shorter lifetime in the atmosphere than carbon dioxide (CO_2), but it is more effective at trapping radiation than CO_2. Over 100 years, the comparative impact of CH_4 is 25 times greater than that of CO_2. The yearly increase in atmospheric methane for 2020, according to NOAA's preliminary research, will be 14.7 parts per billion (ppb), the highest annual increase since systematic observations began in 1983. The global average methane burden in December 2020, the most recent month for which data is available, was 1892.3 parts per billion. That would be a rise of around 119 parts per billion, or 6%, since 2000 [10].
- Nitrous oxide (N_2O) - Nitrous oxide is a colorless gas used to induce drowsiness and pain relief, as well as to make people feel drunk or high. It is the third-highest concentration of greenhouse gases responsible for global warming in our atmosphere, after CO_2 and CH_4. N_2O can last up to 125 years in the atmosphere. Its worldwide concentration levels have risen by 20% from 270 ppb in 1750 to 331 ppb in 2018. Because of human emissions, growth has been the fastest in the last five decades [11].
- Sulfur hexafluoride (SF_6) - Sulfur hexafluoride is a fluorinated synthetic chemical with a molecular structure that is exceptionally stable. Electric utilities rely significantly on SF_6 in electric power systems for voltage electrical insulation, current interruption, and arc quenching in the transmission and distribution of electricity due to its unique dielectric qualities. It is, nevertheless, the most potent greenhouse gas known to date. Over a century, SF_6 is 22,800 times more effective than carbon dioxide CO_2 at trapping infrared light. SF_6 is also a relatively stable molecule, having a 3200-year atmospheric lifespan. As the gas is exhaled, it accumulates in the atmosphere for many centuries in an essentially

undamaged state. As a result, even a small amount of SF_6 can have a significant impact on global warming [12]. From 1995, the worldwide mean concentration of SF_6 has progressively climbed from around 3.5 parts per trillion (ppt) to 10.5 ppt in 2021 (to date), a three-fold increase over 25 years [13].

- Carbon monoxide (CO) - Although carbon monoxide is a very weak direct greenhouse gas, it has significant indirect global warming impacts. CO reduces the quantity of hydroxyl (OH) radicals in the environment by reacting with them. More than half of carbon monoxide emissions are now caused by humans. The highest levels of carbon monoxide are found in locations with a high human population. On a worldwide scale, this means that the northern hemisphere, which is more densely populated, has higher carbon monoxide concentrations than the southern hemisphere. CO emissions are mostly caused by the combustion of biomass and the use of fossil fuels [14].

2.2. Radiative forcing

Along with the growth of GHG, radiative forcing is also increasing. Radiative forcing is a measure of changes in atmospheric energy balance resulting from changes in natural and human factors (e.g., GHG, clouds, surface albedo) to affect the global energy balance and contribute to climate change, and is measured in W/m^2. It is a scientific concept used to count and compare external factors that affect the world's energy balance. To calculate the radiative forcing, expressions from Table 1 are used [15]:

Table 1. Expressions for Calculating Radiative Forcing

Gases	Radiative forcing, ΔF (W/m^2)	Constants
CO_2	$\alpha \ln(C/C_o)$	$\alpha = 5.35$
CH_4	$\beta(M^{½} - M_o^{½}) - [f(M,N_o) - f(M_o,N_o)]$	$\beta = 0.036$
N_2O	$\varepsilon(N^{½} - N_o^{½}) - [f(M_o,N) - f(M_o,N_o)]$	$\varepsilon = 0.12$
Other gases	$\omega(X - X_o)$	depend on gas

Where, $f(M, N) = 0.47\ln[1+2.01\times10^{-5}(MN)^{0.75}+5.31\times10^{-15}M(MN)^{1.52}]$, $C_o = 278$ ppm, $M_o = 722$ ppb, $N_o = 270$ ppb, and $X_o = 0$.

These are empirical formulas derived from atmospheric radiation transmission modeling and are 99% reliable for long-term GHGs in the atmosphere. However, the impact of global short-term pollutants such as aerosols and tropospheric ozone, which are short-lived and spatially unstable in the atmosphere, is uncertain.

2.3. Climate change

2.3.1. Greenhouse gases and climate change

GHG allows sunlight to enter the atmosphere, heating the planet, but then absorbs and re-radiates the Earth's infrared radiation (heat), as shown in the figure. Varying GHGs can have different warming effects on the planet. The ability to absorb energy (their "radiative efficiency") and the length of time they stay in the atmosphere are two critical ways in which these gases differ from one another.

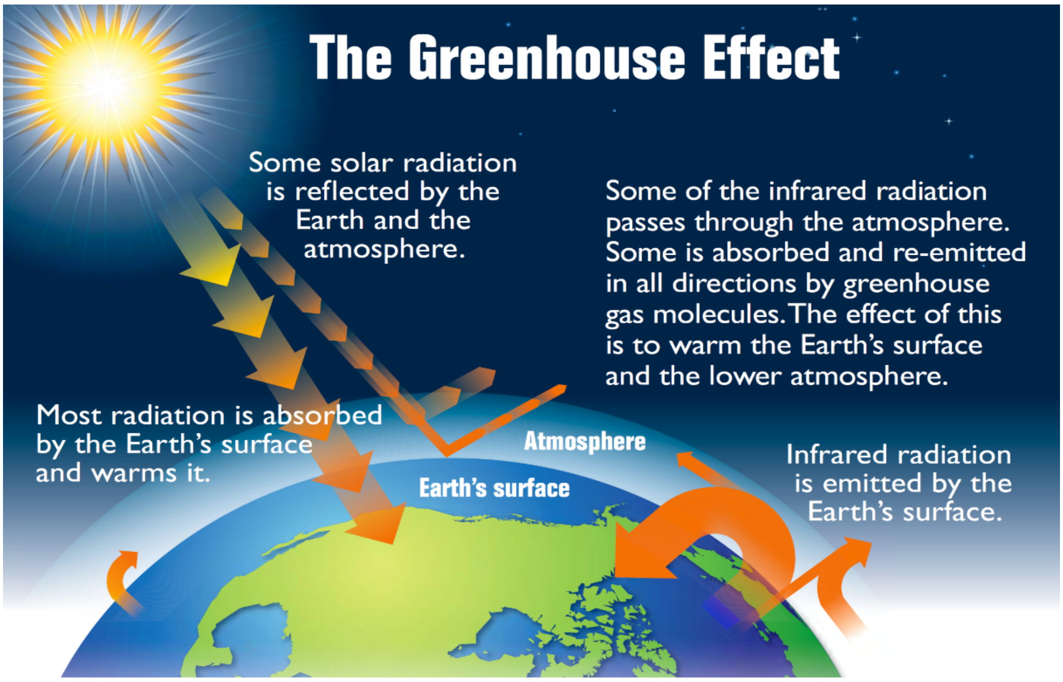

Figure 2. Explanation of greenhouse gas effect

The Global Warming Potential (GWP) was created to facilitate comparisons of different gases' global warming effects. It is a measure of how much energy 1 ton of gas emissions will absorb over a specific length of time in comparison to 1 ton of CO_2 emissions. The greater the GWP, the more a given gas heats the Earth over time when compared to CO_2. The most common period for GWPs is 100 years. Analysts can add up emissions estimates of different gases (for example, to construct a national GHG inventory), and policymakers can evaluate emissions reduction potential across sectors and gases using GWPs [16]. Particularly:

- CO_2: Carbon dioxide which accounts for roughly 76% of worldwide human-caused emissions, is a long-lasting gas. After it is released into the atmosphere, 40% of it is still present after 100 years, 20% after 1,000 years, and 10% after 10,000 years.

- CH_4: Although methane lasts a significantly shorter time in the atmosphere than carbon dioxide (approximately a decade), it has a much greater warming effect. In fact, over 100 years, its global warming impact is 28 times greater than that of carbon dioxide. It accounts for roughly 16% of all human-caused GHG emissions globally.
- N_2O: Nitrous oxide is a potent greenhouse gas with almost a GWP 300 times that of carbon dioxide on a 100-year time scale, and it lasts a little more than a century in the atmosphere on average. It contributes roughly 6% of global human-caused GHG emissions.
- SF_6: Although fluorinated gases are emitted in smaller quantities than other greenhouse gases (about 2% of manufactured global greenhouse gas emissions), they trap far more heat. Indeed, the GWP of these gases can range from hundreds to tens of thousands, and they have extended atmospheric lives, lasting tens of thousands of years in some cases.

Table 2. Global warming potential of greenhouse gases

GHGs	GWP for 100 years
CO_2	1
CH_4	28
N_2O	265
SF_6	22800

Thus, GHGs affect climate in several aspects such as:

- Global warming: As the concentration of greenhouse gases rises, so does the amount of outgoing infrared radiation; as a result, the Earth's climate must shift in some way to restore the balance of incoming and outgoing radiation. Warming is the simplest way for the climate to eliminate excess energy, therefore, this "climatic shift" will entail a "global warming" of the Earth's surface and lower atmosphere. For example: in 2020, Asia experienced the warmest year on record, with a mean temperature 1.39°C higher than the 1981-2010 average. Many significant heat extremes occurred, including a temperature of 38.0°C in Verkhoyansk, Russian Federation, which is provisionally the hottest temperature ever recorded anywhere north of the Arctic Circle [17]. This topic will be discussed in more detail in Chapter 2.3.2.
- Extreme events: Due to human-caused greenhouse gas emissions, the Earth's lower atmosphere is growing warmer and moister. This increases the energy available to storms and other extreme weather phenomena. The types of events most strongly tied to

temperatures, such as heatwaves and sweltering days, are becoming more likely, which is consistent with theoretical predictions. In addition, heavy rain and snowfall events (which enhance the risk of floods) are growing increasingly often. The atmosphere can contain an additional 4% of water vapor with every additional –17.2°C of warming. As a result, when this more water vapor condenses into precipitation, it results in heavier rain – or, if the temperature is cold enough, heavier snow. The quantity of precipitation dropping in the heaviest 1% of all events is increasing across the United States, with increases of 55% in the Northeast and 42% in the Midwest since 1958 [18].

- Sea level rise: Sea level will increase due to two processes if global warming occurs. For starters, the thermal expansion of seawater causes the sea level to rise as temperatures rise. Second, water from melting glaciers and ice sheets in Greenland and Antarctica would add to the ocean's water supply. Between 1990 and 2100, the average sea level is expected to rise by 0.09 to 0.88 meters [19].
- Desertification: Natural temperature oscillations and global warming as a result of human-caused greenhouse gas emissions are examples of direct causes of desertification [19]. According to a study published in early January 2018, global warming is hastening desertification, which could affect between 24% and 32% of the world's land area by 2050. The planet is already experiencing desertification, and global warming is hastening the process. As a result, the researchers anticipate that aridity and desertification will affect 24% of the land surface in 2050 if temperatures rise 1.5°C over pre-industrial levels. This proportion jumps to 32% if the world warms by 2°C by 2050 [20].

2.3.2. Global warming

Global warming is a concept that refers to a potentially severe increase in the Earth's yearly average global surface temperature. Even though global warming has not been uniform, the rising trend in global average temperature reveals that more locations are warming than cooling. Since 1880, the total land and ocean temperature has grown at an average pace of 0.08°C every decade [21]. If our climate changes due to this temperature change, we can expect other changes as well. The distribution of rainfall may shift, and the frequency of extreme weather events like hurricanes and typhoons may increase. Most scientists assume that increasing levels of CO_2 and other GHGs in the Earth's atmosphere are to blame for this trend [22]. Despite the fact that global warming has not been uniform, the rising trend in global average temperature reveals that more locations are warming than cooling. Since 1880, the average rate of increase for land and ocean temperatures has been 0.08ºC per decade; however, the average rate of increase since 1981 (0.18°C) has been more than doubled that rate. All ten of the warmest years on record have occurred since 2005, with seven of them occurring since 2014. Looking back to 1988, a pattern emerges: except for 2011, each new year becomes one of the top ten warmest on record at the moment, but it is eventually supplanted when the "top ten" window swings forward in time [23]. How much carbon dioxide and other greenhouse gases we emit in the coming decades will determine how much warming the Earth will experience in the future. Our current actions, such as burning fossil fuels and cutting forests, contribute around 11 billion metric tons of carbon to the atmosphere each year. According to a report by the United Nations Environment Programme (UNEP), if countries keep their recent promises to reduce emissions by 2030, the world is likely to warm up by at least 2.7°C this century. This exceeds the 1.5°C temperature rise that has been agreed upon worldwide [24]. In Figure 3, projections for global temperature changes in various scenarios until 2099 are shown. The estimated future trends reveal the observed and anticipated rises in temperatures in most parts of the world. The top maps show the estimated climate change for a 2°C global average change, the middle figure for a 3°C change, and the bottom figure for a 4°C change [25].

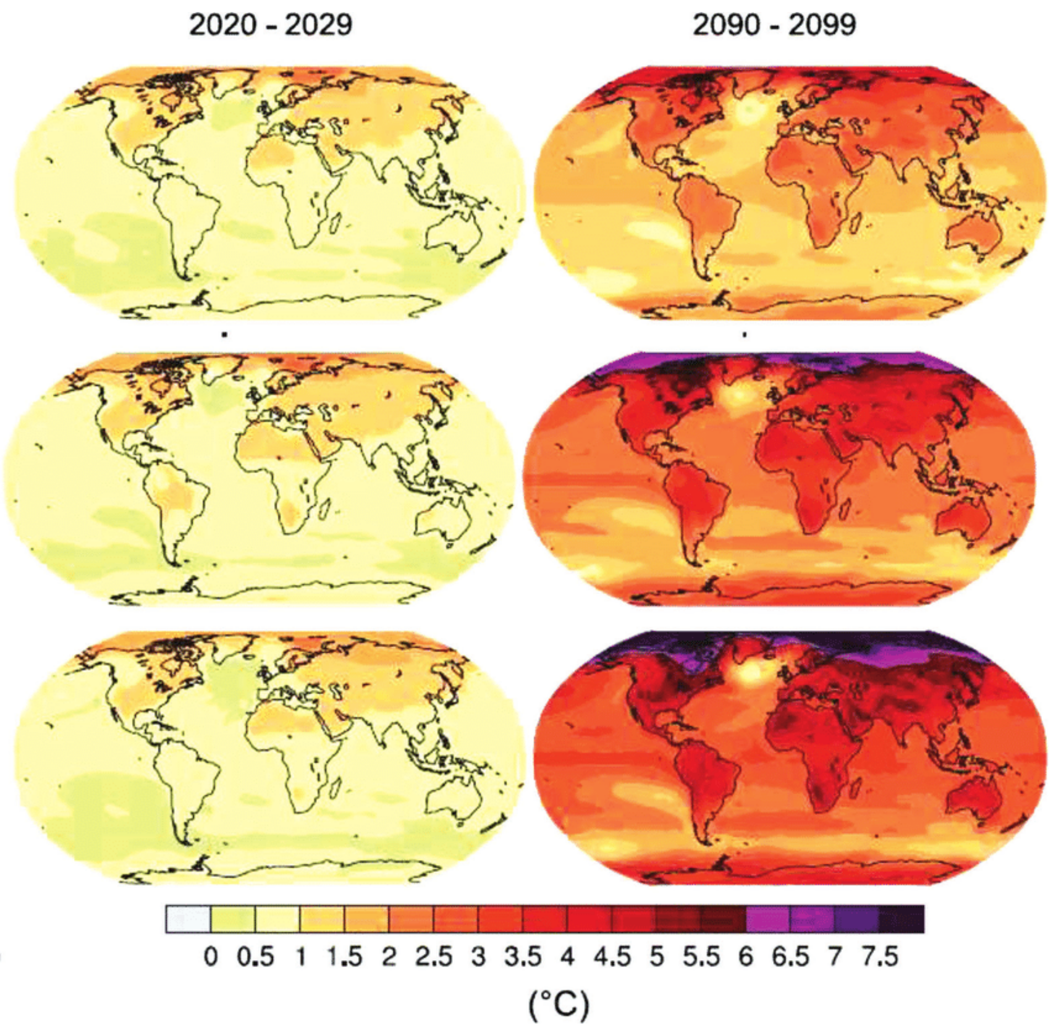

Figure 3. Projections for global temperature changes

2.3.3. Climate change in Mongolia

Mongolia is one of the world's largest landlocked countries, spanning 1.564 million km² and stretching between the latitudes of 41°35'N and 52°09'N and the longitudes of 87°44'E and 119°56'E. The longest distance is 2,392 kilometers from west to east and 1,259 kilometers from north to south. 1,580 meters above sea level is the average altitude. Mongolia is divided into 21 aimags for administrative purposes. Aimags are separated into soums, and there are over 330 of them. Long and cold winters, dry and scorching summers, minimal precipitation, considerable temperature swings, and a comparatively high number of sunny days (an average of 260) per year describe Mongolia's climate. As a result, not only are there four separate seasons, but also distinct months inside each of them.

The average annual air temperature warmed by 1.9°C between 1940 and 2004. Warming was 1.5-1.6°C in the southern and eastern regions, and 2.0-2.3°C in the western and central regions (Figure 4). Warming is more pronounced in the cold season, with an average increase of 3.6°C in winter and 1.4-1.9°C in spring and autumn. A recent report released by the Information and Research Institute for Meteorology, Hydrology and Environment (IRIMHE), Mongolia, presented that the average annual air temperature in Mongolia has increased by 2.25°C between 1940 and 2019. The greatest warming occurred in Uvs aimag, south of Zavkhan, and southwest of Khuvsgul by 2.5 to 2.8°C [26]. More specifically, in Dornogovi aimag, one of 21 aimags of Mongolia, the average annual air temperature is warmed up 1.9-2.0°C in the central and eastern parts of the country and 1.7°C in the northern part of the country. Due to the seasonality, the average annual air temperature in the whole aimag was 1.7-2.0°C, 0.8-2.4°C in summer, and 0.2-1.0°C in winter [27].

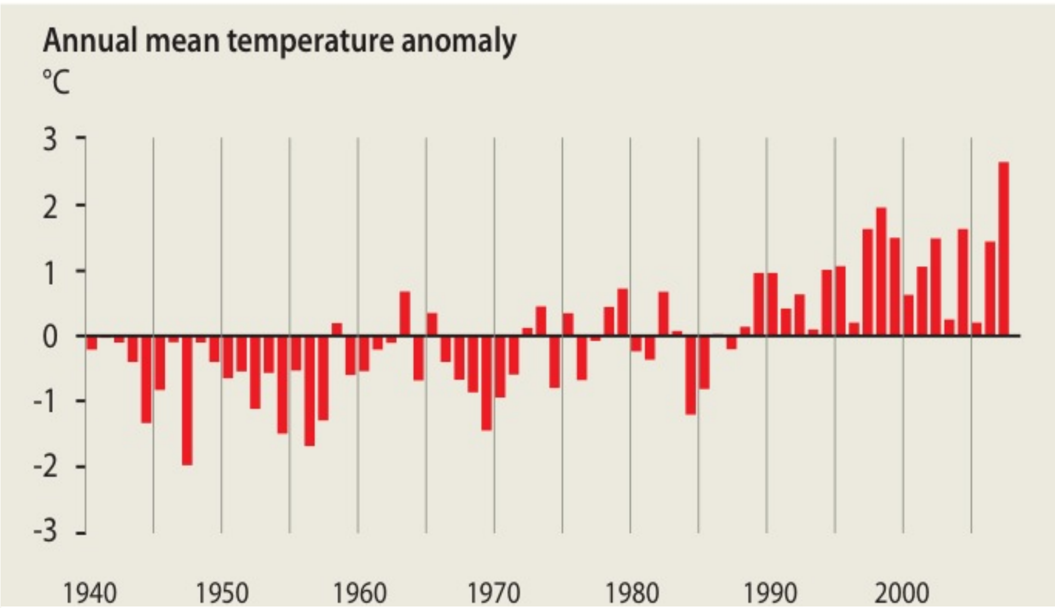

Figure 4. Annual mean temperature anomaly

3. Material and Methods

3.1. Monitoring network, data

Data used in this work are taken from the global monitoring network within the Global Monitoring Laboratory (GML) of the National Oceanic and Atmospheric Administration (NOAA). The GML was initiated in 1972 and conducts three main types of research:

- greenhouse gas and carbon cycle feedbacks
- changes in clouds, aerosols, and surface radiation
- recovery of stratospheric ozone

The laboratory aims to acquire, evaluate, and make available accurate, long-term records of atmospheric gases, aerosol particles, clouds, and surface radiation in a manner that allows the causes and consequences of change to be understood [28].

The GML operates the Global Greenhouse Gas Reference Network, which measures the atmospheric distribution and trends of the three main long-term factors of climate change – carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as carbon monoxide (CO), an important indicator of air pollution. The atmospheric greenhouse gas monitoring is made at 87 points in 37 countries as shown in Figure 5.

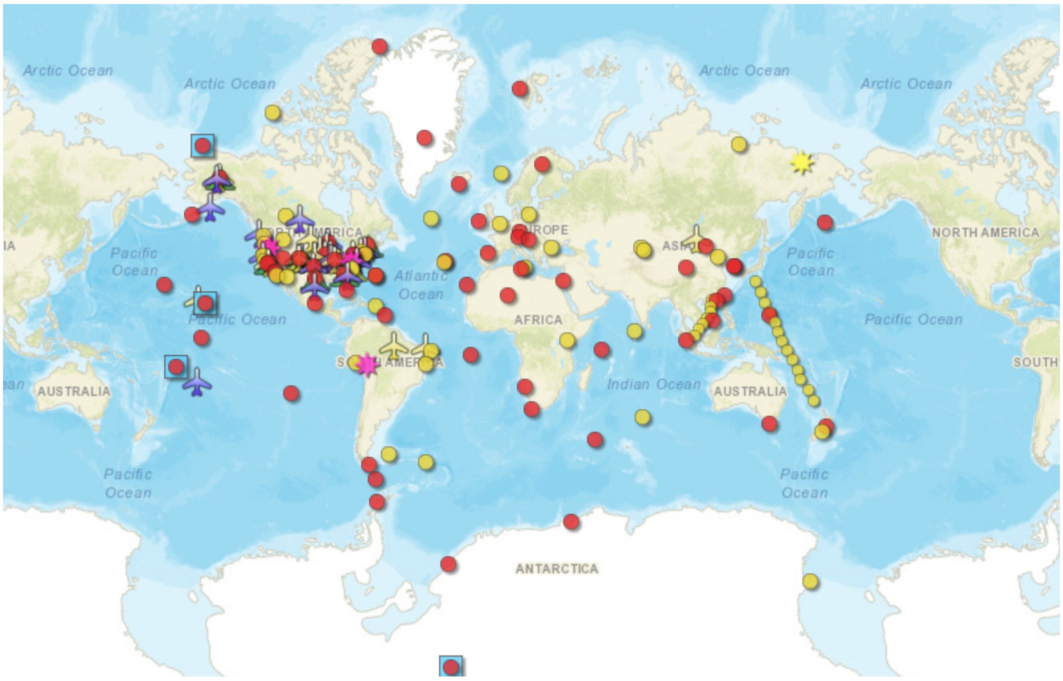

Figure 5. Greenhouse gas monitoring sites of NOAA

3.1.1. Greenhouse gases data

At Ulaan-Uul station, the air is collected and packed in special glass cylinders 1-2 times per week. Because air samples are taken in pairs, they usually travel in pairs to the sampling stations. The numbers on the flasks are used to record whether the flask is in the field or the lab in the Flask Logistics Lab's database. To protect the glass, each flask is wrapped in tape or plastic. The two flasks are housed in a casing with a battery-powered pump and connected to a single air intake tube. The air intake tube's opposite end runs up a long pole that telescopes out of the case to collect more pure samples. Samples can be taken with two flicks of a switch. One flick flushes the glass of the synthetic air with which they are filled in a lab (Figure 6a). Another flick of the switch allows the air sample to be collected. Moreover, all air flasks are shipped in a foam-cushioned box to prevent damage (Figure 6c). In the end, all of the results are produced by NOAA and given on its official site. The availability of the data is shown in Appendix 1.

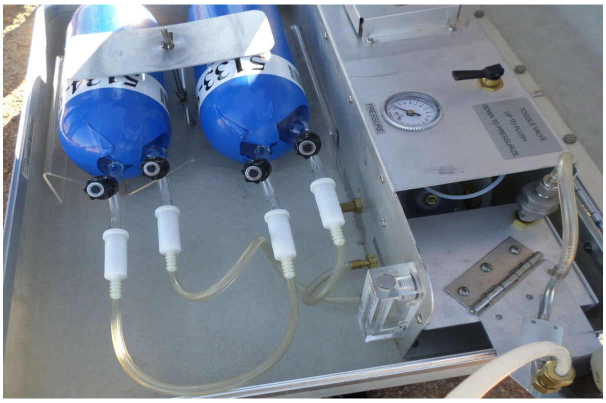

Figure 6. (a) (b) Process of GHG sampling (c) Shipping box used for transporting samples to the NOAA

3.1.2. Meteorological data

Furthermore, temperature data are taken from the weather station operated within the national monitoring network, which is located in Erdene soum, Dornogovi aimag, of the National Agency for Meteorology and Environmental Monitoring. This station has a 10-meter weather measurement tower as shown in Figure 7. Every 2 meters, it has temperature and wind sensors. As for the Mongolian radar standard, sensors should be placed in 2 meters and measure the data. However, to send and to keep pace with the world, sensors are settled every 2 meters until the top.

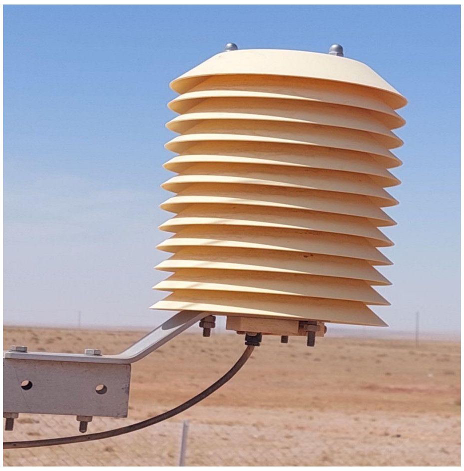

Figure 7. (a) Monitoring mast at the Erdene soum's station (b) temperature sensor

3.2. Study area

One of the monitoring sites within the Global Greenhouse Gas Reference Network of the NOAA is located in Erdene soum of Dornogovi aimag, Mongolia. The NOAA Global Monitoring Laboratory has been measuring greenhouse gases at Ulaan-Uul station (44.45°N, 111.10°E, 914 m) in Erdene soum since 1992 (Figure 8). The soum is 100 km from the aimag center, 600 km from Ulaanbaatar, far from other soums, and is representative of remote areas, which are characterized by low population and underdeveloped industrialized activity.

Moreover, the Erdene soum is elevated at 966 m above sea level and far from any coast. The territory of the soum is suitable for livestock breeding in the Gobi steppe and hills. It is rich in natural resources such as high-quality clay, sand, copper, and gypsum, and plants such as saxaul, elm, sagebrush, leek, and bridle grow. In mountainous areas, there are argali and rams, and in most areas, there are fur-bearing animals such as foxes, wolves, corsac deer, lynx, and badgers, as well as endangered species such as wild ass and black-tailed deer. As for the climate, it is arid and warm. The continental climate is extreme, with an absolute temperature of 33.6°C and cold winters but hot summers. The total annual precipitation is 193.3 mm, of which liquid precipitation is 169.4 mm and solid precipitation is 23.9 mm.

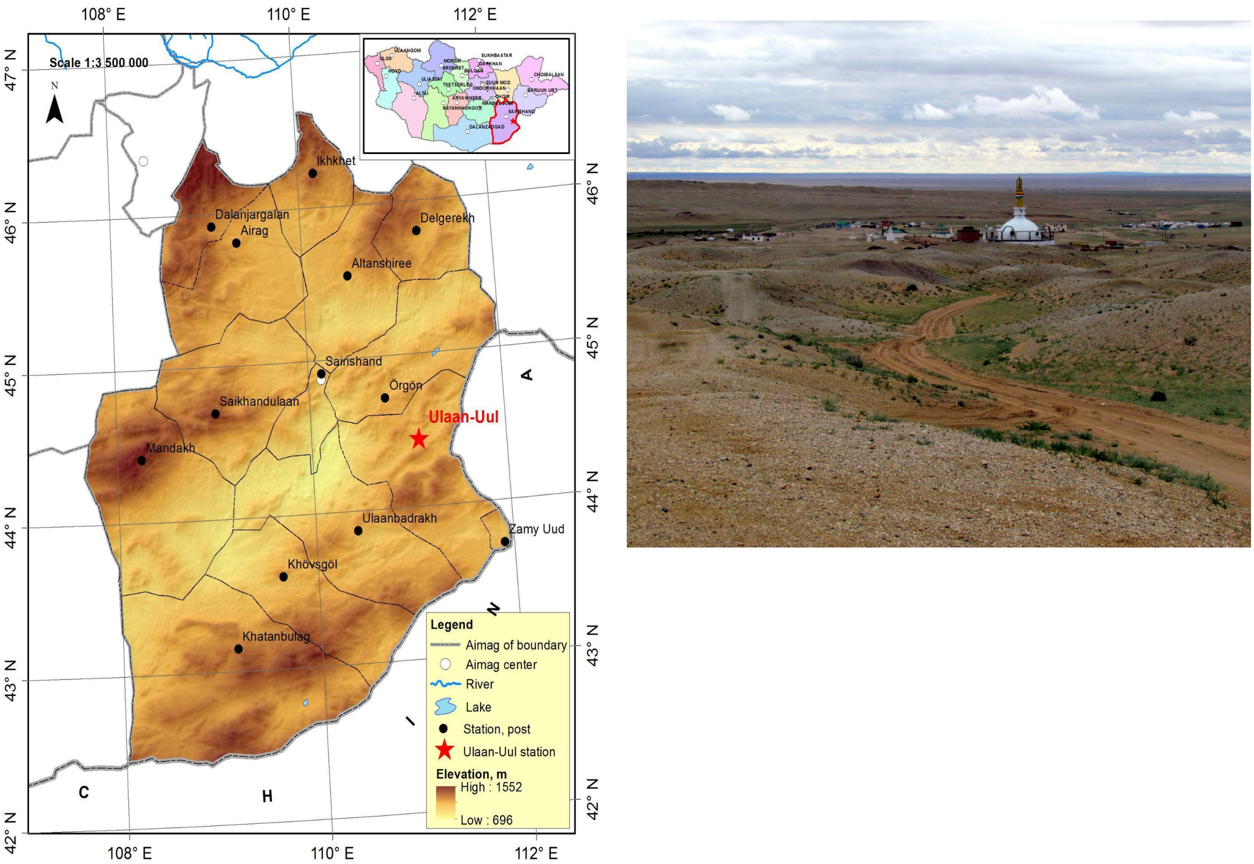

Figure 8. (a) Dornogovi aimag, Ulaan-Uul station (b) Uwgun stupa built in 2011 in Erdene soum

4.Results

4.1. Trends and temporal characteristics of greenhouse gases

Figure 9 shows the time series of concentrations of greenhouse gases in an arid and semi-arid area of Mongolia over the last 29 years based on the results of collected samples at Ulaan-Uul station from 1992 to 2020 (from April 1997 to 2020 for N_2O and SF_6).

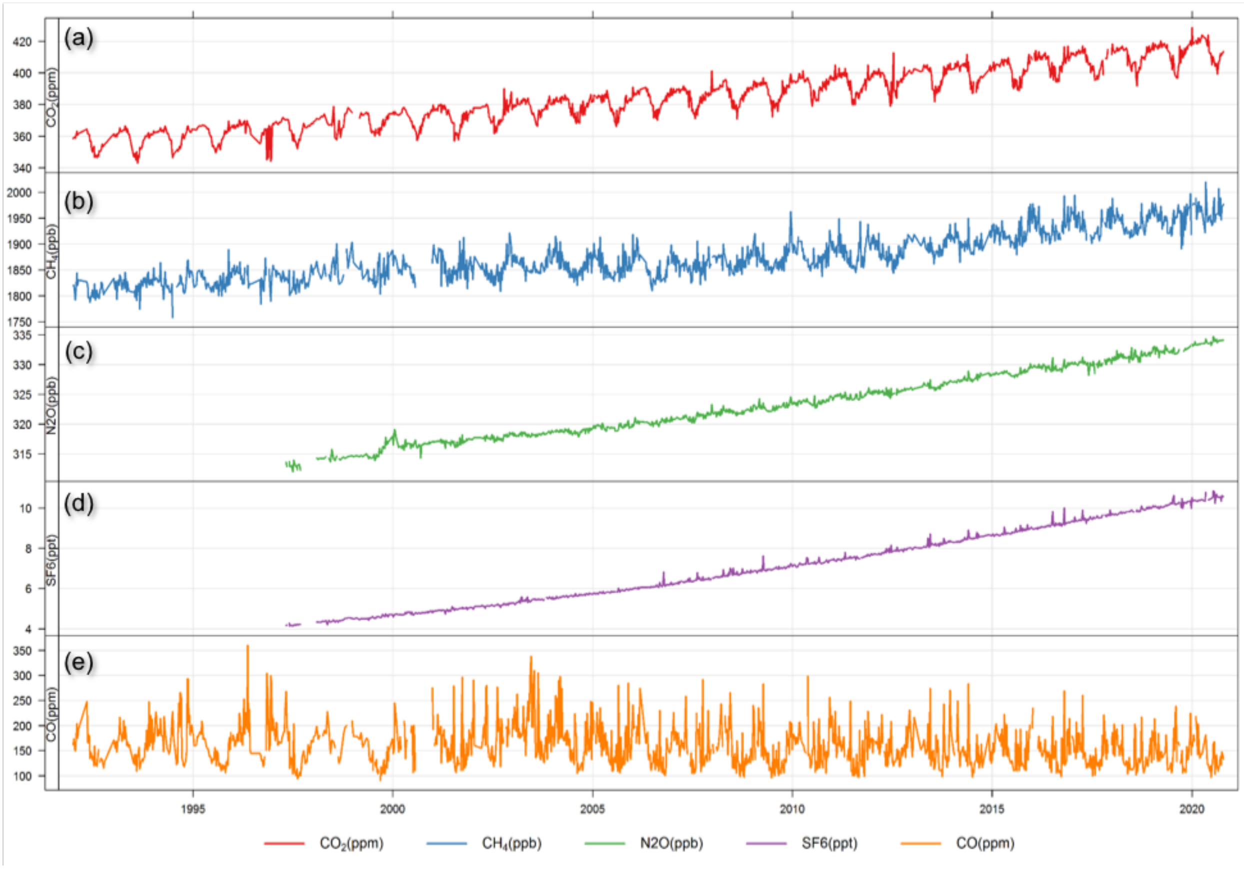

Figure 9. Time series of GHG measured at Ulaan-Uul station in 1992-2020

It is clearly seen that during the measurement period, concentrations of CO_2, CH_4, N_2O, and SF_6 gases are steadily increasing. Namely, CO_2 increased from 354.7 ppm to 413.79 ppm or by 16.7%, CH_4 increased from 1808.5 ppb to 1964.1 ppb or by 8.6%, N_2O increased from 313 ppb to 333.7 ppb or by 6.6%, SF_6 gas concentration increased from 4.2 ppt to 10.5 ppt or by 150%, while CO gas concentration decreased by 4.9%. The global average concentration of CO_2 exceeded 400 ppm in 2015 and similarly, it reached 401.9 ppm at the Ulaan-Uul station in the same year. The growth rate of CO_2, CH_4, N_2O, and SF_6 has averaged 0.6%, 0.3%, 0.3%, and 4.1% per year (from 1992 to 2020), respectively.

The average concentrations of greenhouse gases measured at the Ulaan-Uul station are compared with global averages:

- The global CO_2 concentration rises continuously from 356.8 ppm to 411.6 ppm during the period 1992-2020. The CO_2 concentration at the Ulaan-Uul rises approximately linearly. However, the global average is slightly higher than that at the Ulaan-Uul station. For example, in 2020, the average global concentration of CO_2 was 414.5 ppm, which is 0.03 ppm (0.07%) higher than at the Ulaan-Uul station.
- As for CH_4 gas, according to the NOAA, the concentration of methane in the atmosphere has increased since 2011. As of December 2020, the average global concentration was 1892.2 ppb, which is 17.4 ppb (0.9%) higher than at the Ulaan-Uul station.
- The global average N_2O gas content increased from 270 ppb in 1750 to 331 ppb in 2018, while the Ulaan-Uul station shows 322.1 ppb (2.8%) in 2018.
- As of 2020, the global average concentration of SF_6 gas was (10.4 ppt) 1% higher than the Ulaan-Uul average.

Mongolia's and the global averages of the greenhouse gases continue to rise for SF_6, CO_2, CH_4, and N_2O, while CO is the only one, which declines slightly. This characteristic is also found in the global average

Table 3. General changes, average and maximum (or minimum) values for each GHG concentration measured at Ulaan-Uul station between 1992 and 2020.

	CO_2	**CH_4**	**N_2O**	**SF_6**	**CO**
Slope	y=0.0057x+161.51 m=0.0057	y=0.0127x+1379.2 m=0.0127	y=0.0022x+236.39 m=0.0022	y=0.0008x-23.797 m=0.0008	y=–0.0028x+266.87 m=–0.0028
Average value	384.6 ppm	1874.8 ppb	323.4 ppb	7.1 ppt	158.7 ppm
Maximum value (minimum for CO)	428.6 ppm	2019.8 ppb	334.7 ppb	10.9 ppt	90.6 ppm

Table 3 provides the change, average, and maximum (or minimum) values of greenhouse gas concentrations at the Ulaan-Uul station during the period 1992 to 2020. Ten maximum values of CO_2 concentration were observed in 2020. The highest value of CH_4 was also observed in 2020, with an 0.0127 ppb slope, the highest of any other greenhouse gas. Likewise, N_2O and SF6 had positive slopes of 0.0022 ppb and 0.0008 ppt, respectively. On the other hand, the slope of CO was negative which is –0.0028 ppm.

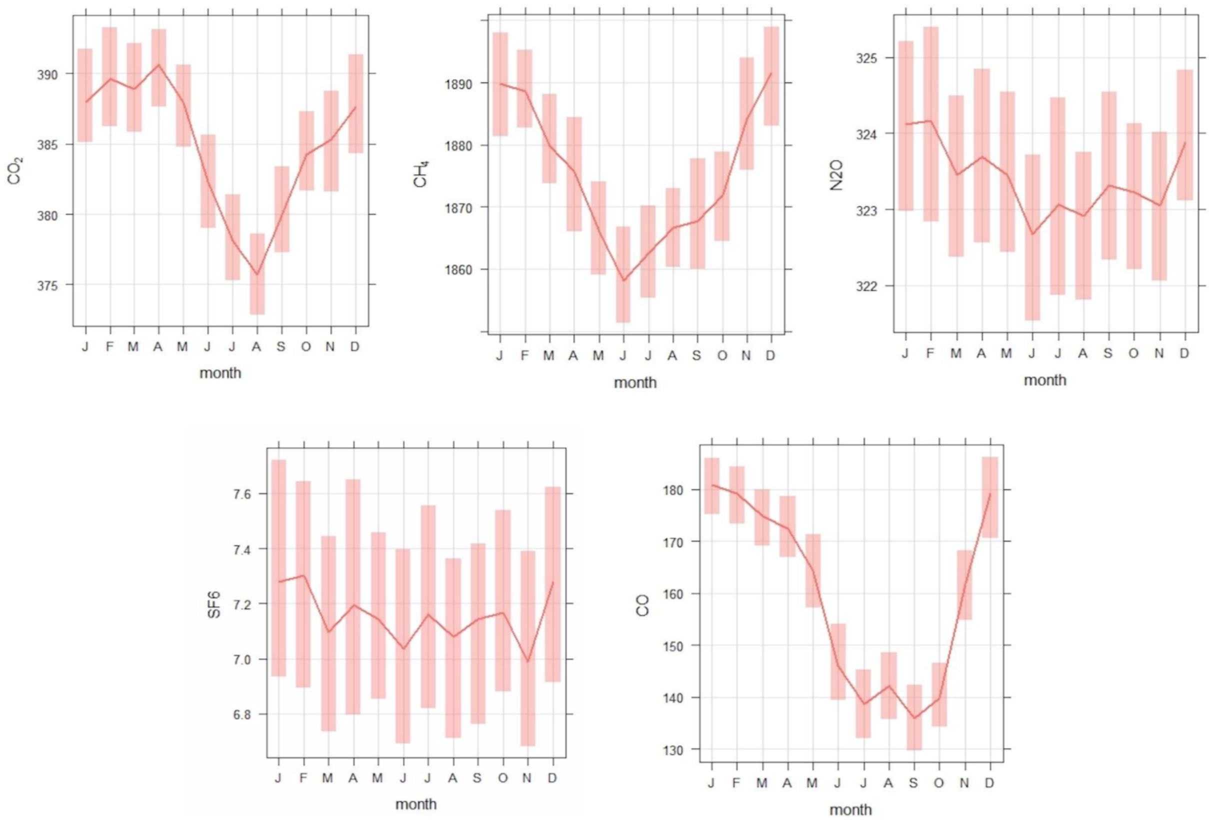

Figure 10. Seasonal variations of GHG measured at Ulaan-Uul station in 1992-2020

To note, a global consensus was made that increased carbon emission leads to rapid global warming and such a sharp increase in greenhouse gases in recent times is greatly attributed to anthropogenic activities. The seasonal variation of each greenhouse gas is shown in Figure 10. The seasonal variations are clearly shown for CO_2, CH_4, and CO. The maximum CO_2 reached 428.6 ppm in the winter of 2020 and the minimum was 342.9 ppm in the summer of 1993. In general, the seasonal variations of CO_2 are associated with the combined influence of anthropogenic emissions and exchanges between the land biosphere and atmosphere. For example, in the winter of the northern hemisphere, fossil fuel burning (e.g. coal-fired heating and cooking) and biomass burning sharply increase the emissions and contribute to higher CO_2 and CH_4 mole fractions in the atmosphere. In addition, in the summer months, the CO_2 content in the atmosphere is the lowest due to the effective photosynthesis process, while in the winter months photosynthesis process is inhibited. Although the amplitudes of the N_2O and SF_6 gases are not very large, they tend to be as high in winter and low in summer as other gases. Lastly, CO reached its maximum of 309.4 ppm in 1993 and a minimum of 90.7 ppm in 1999 and the difference between maximum and minimum concentrations is the highest among other greenhouse gases.

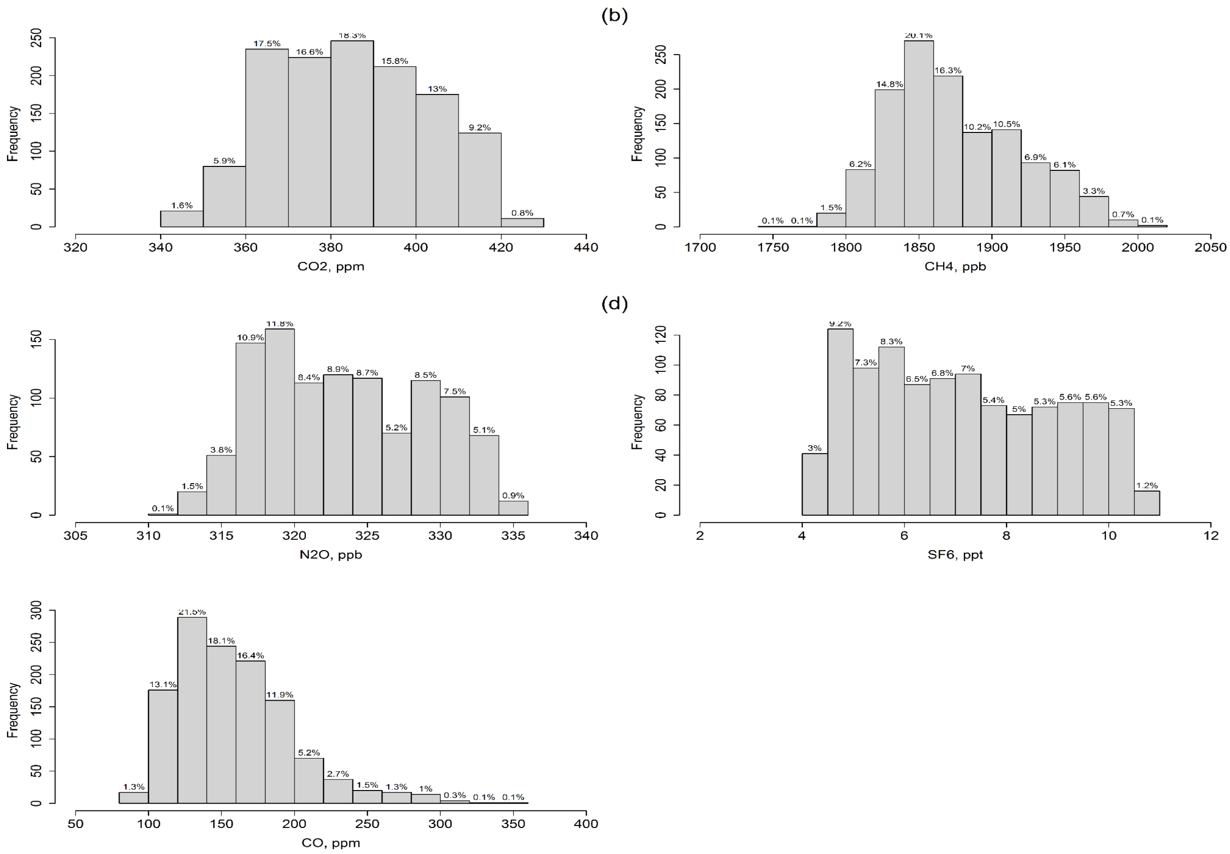

Figure 11. Frequency distribution of GHG measured at Ulaan-Uul station in 1992-2020

Figure 11 shows the frequency distribution of each greenhouse gas concentration using measurements made continuously since 1992.

- 56.3% of CO_2 gas is 380-420 ppm,
- 51.2% of CH_4 gas is 1830-1880 ppb,
- 48.7% of N_2O gas is 318-320 ppm,
- 45.1% of SF_6 gas is 4.0-7.8 ppt,
- 81% of CO gas is observed in the range of 100-200 ppm. The CO concentrations at other regional sites such as Tae-ahn Peninsula in Korea (TAP), Mt. Waliguan in China (WLG), and Ulaan-Uul from 1991 to 2008 are compared by Kim et al. (2010) [29]. Since CO is affected by large-scale air pollution transport, CO dispersion at TAP shows a wide range. Unlike UUM and WLG, the comparatively low CO contents at TAP imply travels from the

oceanic background airflows sector. CO concentrations in UUM, are in the middle of the WLG and TAP distributions.

Although greenhouse gases except CO have been continuously increasing during the measurement period, the growth rate varies over time. To study GHG growth in more detail, the 29-year-long measurements are divided into three periods and analyzed.

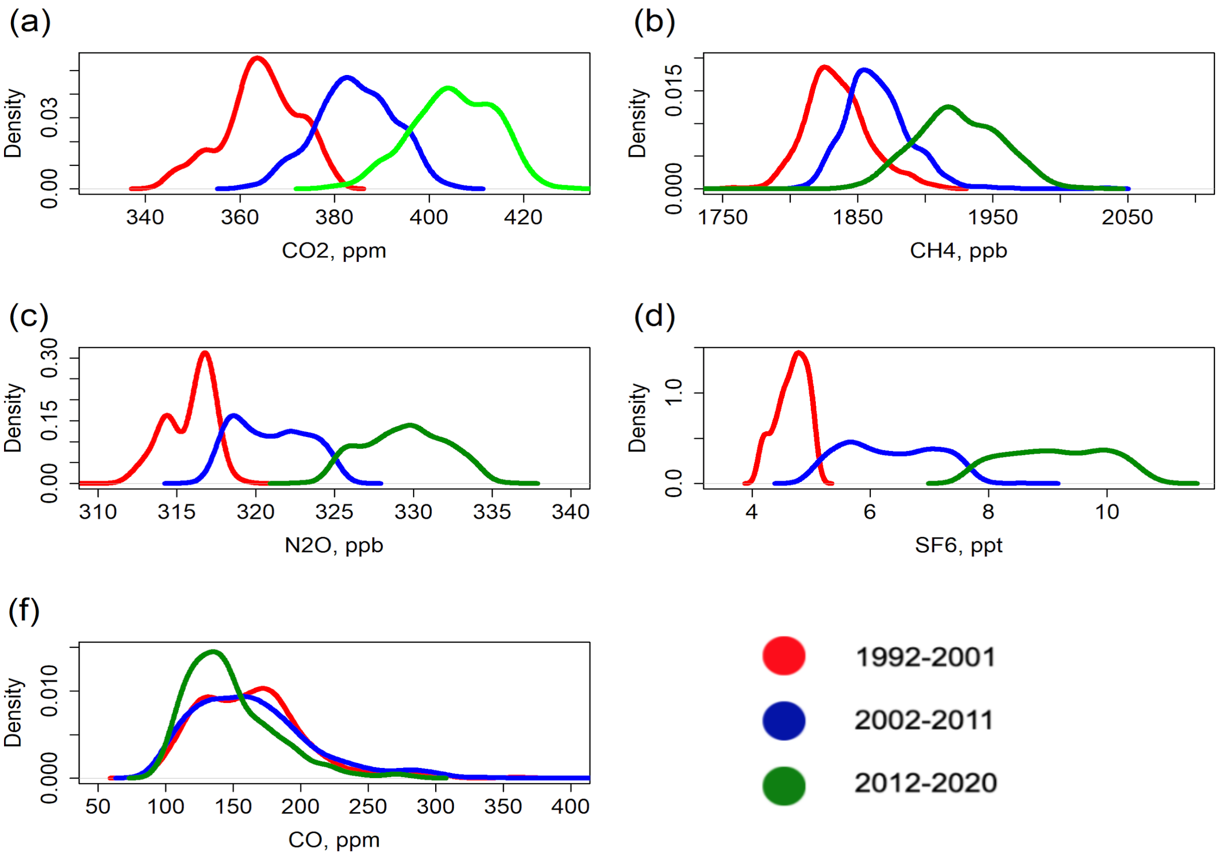

Figure 12. Density curves of GHG measured at Ulaan-Uul station in 1992-2020

Figure 12 shows the density curves of the greenhouse gases during the three periods. It is evident that the greenhouse gases over the past decade are distributed in greater ranges relative to the first and second decades with:

- The modes of CO_2 concentrations in three decades change from 364.4 ppm to 405.2 ppm. It showed an 11.2% growth of modes in Mongolia. In the 1990s it started from 354.7 ppm to 368.1 ppm which showed a 3.8% growth. In addition, last ten years, the increase of CO2 Concentration has risen by 4.8%. Globally, CO_2 levels in the atmosphere, for example, have risen by an average of 1.85 ppm per year over the last 41 years (1979-2020). CO2 levels are rising faster than ever before; after averaging around 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the rate has accelerated to 2.4 ppm per year in the recent decade (2009-2020). The yearly CO2 increase from 1 January 2020 to 1 January 2021 was 2.50±0.08 ppm, which is slightly more than the preceding decade's average and significantly greater than the prior two decades [9].

- The modes of CH_4 concentrations in three decades change from 1834.9 ppb to 1924.5 ppb or a growth of 4.9% in mode was seen. For the global average, from 1983 to 1999, the rate of growth of methane decreased, indicating that its concentration was approaching a steady-state. Significant interannual fluctuation in growth rates is superimposed on this drop. The atmospheric CH_4 burden was practically steady from 1999 to 2006, but since 2007, CH_4 has been growing again. The causes of the rise are unknown, but in the early years, mild temperatures in the Arctic in 2007 and greater precipitation in the tropics in 2007 and 2008 played a role. After 2008, isotopic measurements suggest that microbial emissions will continue to rise (e.g., likely from wetlands or agriculture). Since 2015, the worldwide annual growth in methane has accelerated, with an average annual increase of 9.7±3.3 ppb per year projected through 2020, up from 6.4±2.9 ppb per year between 2008 and 2014. The yearly methane increase in 2020 was 15.85±0.47 ppb, the highest annual increase since NOAA's continuous monitoring began in 1983.
- In Mongolia, the modes of N_2O concentrations in three decades increased from 317.7 ppb to 324.7 ppb or 2.2% from the second to third decade. Global, the N_2O burden in the atmosphere continues to rise over time. Furthermore, the annual increase in nitrous oxide's atmospheric burden is increasing, averaging 1.0 ppb per year during the last decade. In 2020, the annual growth was the highest ever recorded since records began.
- SF_6 content increased from 4.7 ppt to 9.2 ppt or 95.7%. It should be noted that the measurement of SF_6 started in 1997. Thus the first decade shows slightly higher value than those in the next two decades.
- CO distribution over the last decade was found in a lower concentration range compared to previous decades.

The results of this subchapter are introduced in the “Applied science 2021” fifth scientific conference organized by the National University of Mongolia and published in the conference proceedings (See Appendix 2).

4.2. Comparisons of GHG concentrations

4.2.1. Comparison with other stations in the world

GHG observed at the Ulaan-Uul, Mongolia (UUM) is compared with that at stations located in different locations of the world. These are Syowa Station, Antarctica (SYO), Alert, Nunavut, Canada (ALT), Hegyhatsal, Hungary (HUN), and Mauna Loa, Hawaii, United States (MLO). The time coverage at those stations is between 1986 and 2020.

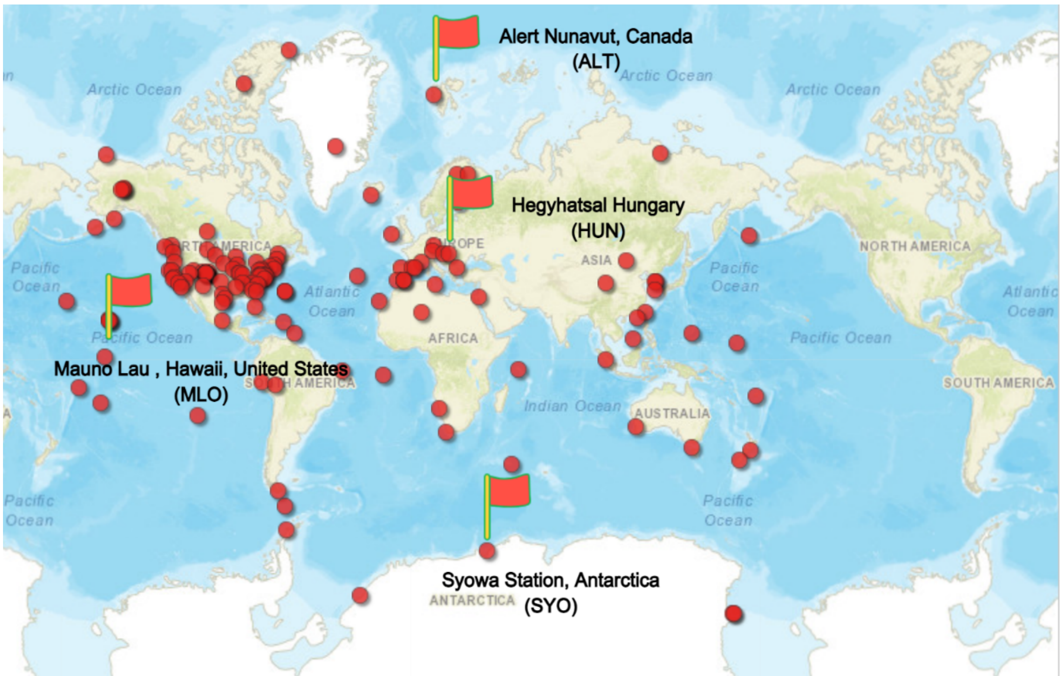

Figure 13. Locations of ALT, HUN, MLO, and SYO stations

- Syowa Station, Antarctica (SYO): The East Ongle Island in Eastern Antarctica, or south of the western Indian Ocean, is home to Syowa Station. The island is approximately 4 km from the Antarctic Continent, and as a result of this distance, the climate is milder than at other Antarctic outposts. For ten months, the ground is covered in snow, which supports some exceptionally resilient flora. When the ice melts, mosses, lichens, and liverwort emerge. The average annual temperature is around –10°C and the average annual wind speed is 6.4 m/s.
- Alert, Nunavut, Canada (ALT): It is situated on the northeastern extremity of Ellesmere Island in Nunavut, distant from the Northern Hemisphere's major industrial centers. The Observatory's annual mean air temperature is –18°C, with monthly mean air temperatures ranging from 3°C in August to below –30°C from December to the end of March.
- Hegyhatsal, Hungary (HUN): Antenna Hungaria Corp. owns the TV and radio transmission tower, which is located in a flat region of western Hungary. Agricultural areas (mainly crops and fodder of annually changing varieties) and wooded patches surround the tower. Within 10 km of the tower, the distribution of vegetation types (60% arable land, 30% forest and woodland, and 10% other) is similar to the average for the Western Hungarian Landscape Unit or the entire country (85% of the area is cultivated, 77% of which is agricultural and 23% is forest).

- Mauna Loa, Hawaii, United States (MLO): Mauna Loa Observatory is located at an elevation of 3397 meters on the northern face of Mauna Loa volcano near 200 degrees north on the island of Hawaii. Mauna Loa Observatory, which was founded in 1957, has evolved into the world's premier long-term atmospheric monitoring station and is where the ever-increasing quantities of global atmospheric CO_2 were determined.

The change in GHG concentration measured at those five stations between 1986 and 2020 is shown in Table 4. Generally, as mentioned before, global averages of the GHG continue to rise for SF_6, CO_2, CH_4, and N_2O, while CO is the only one, which declines slightly. This characteristic is also found in the following stations. Firstly, CO_2 and CH_4 increased the highest in SYO by 18.6%. According to a new study, sedimentary basins beneath the Antarctic Ice Sheet contain massive amounts of organic carbon, which works in tandem with bacteria to make methane. The organic carbon is metabolized by the bacteria into carbon dioxide and methane gas. Secondly, N_2O increased the most in MLO which was 6.5%, however, SYO, ALT, and HUN stations data are close to the MLO. That means all over the world, N_2O is increasing equally. Thirdly, CO is the only greenhouse gas that is decreasing all over the world. From 1992 to 2020, the most significant decline showed in HUN station. On the contrary, CO concentration at UUM had the smallest decrease compared to the other stations.

Table 4. Change in GHG concentrations measured at different stations

GHG	Ulaan Uul, Mongolia (UUM) /1992-2020/	Syowa Station, Antarctica (SYO) /1986-2020/	Alert, Nunavut, Canada (ALT) /1992-2020/	Hegyhatsal, Hungary (HUN) /1993-2020/	Mauna Loa, Hawaii, United States (MLO) /1992-2020/
CO_2	16.7%	18.6%	16.6%	16.5%	16.1%
CH_4	8.6%	11.4%	8.0%	7.1%	8.4%
N_2O	6.6%	6.4%	6.3%	6.2%	6.5%
SF_6	150%	160.8%	137.8%	130.9%	153.7%
CO	–4.9%	–5.8%	–10.5%	–16.5%	–10.4%

So, the trends of the changes in GHGs are similar among stations. But the rates differ in locations.

4.2.2. Comparison with stations in East Asia

Furthermore, to make a more precise comparison, discrete air sample measurements of greenhouse gases were analyzed at the following East Asian monitoring sites: Ulaan-Uul, Mongolia (UUM), Mt. Waliguan, China (WLG), and Tae-ahn Peninsula, Korea (TAP) (Figure 14), from 1992 to 2020.

Figure 14. Locations of UUM, WLG, and TAP stations

- Mt. Waliguan, China (WLG): The station is located on the Tibetan plateau in Western China, at the summit of Mt. Waligaun. –0.9°C is the annual average temperature and the average annual wind speed is 4.6 m/s. The annual precipitation averages 350 mm (mainly in the summer months). Mount Waligaun is a rural location far from any significant industrial sources. Quiapuqia, with a population of 30,000 people, is the closest large settlement, located 30 km to the west. The surrounding area is grassy (there are no trees), and the general region is thinly vegetated. In 1999, the structure was rebuilt.
- Tae-ahn Peninsula, Korea (TAP): The sampling site is located on the western tip of central Korea. The Tae-ahn Peninsula, South Korea, sample site is run in collaboration with the Korean National University of Education. In late 1990, the first NOAA/CMDL flask air samples from Tae-ahn were taken.

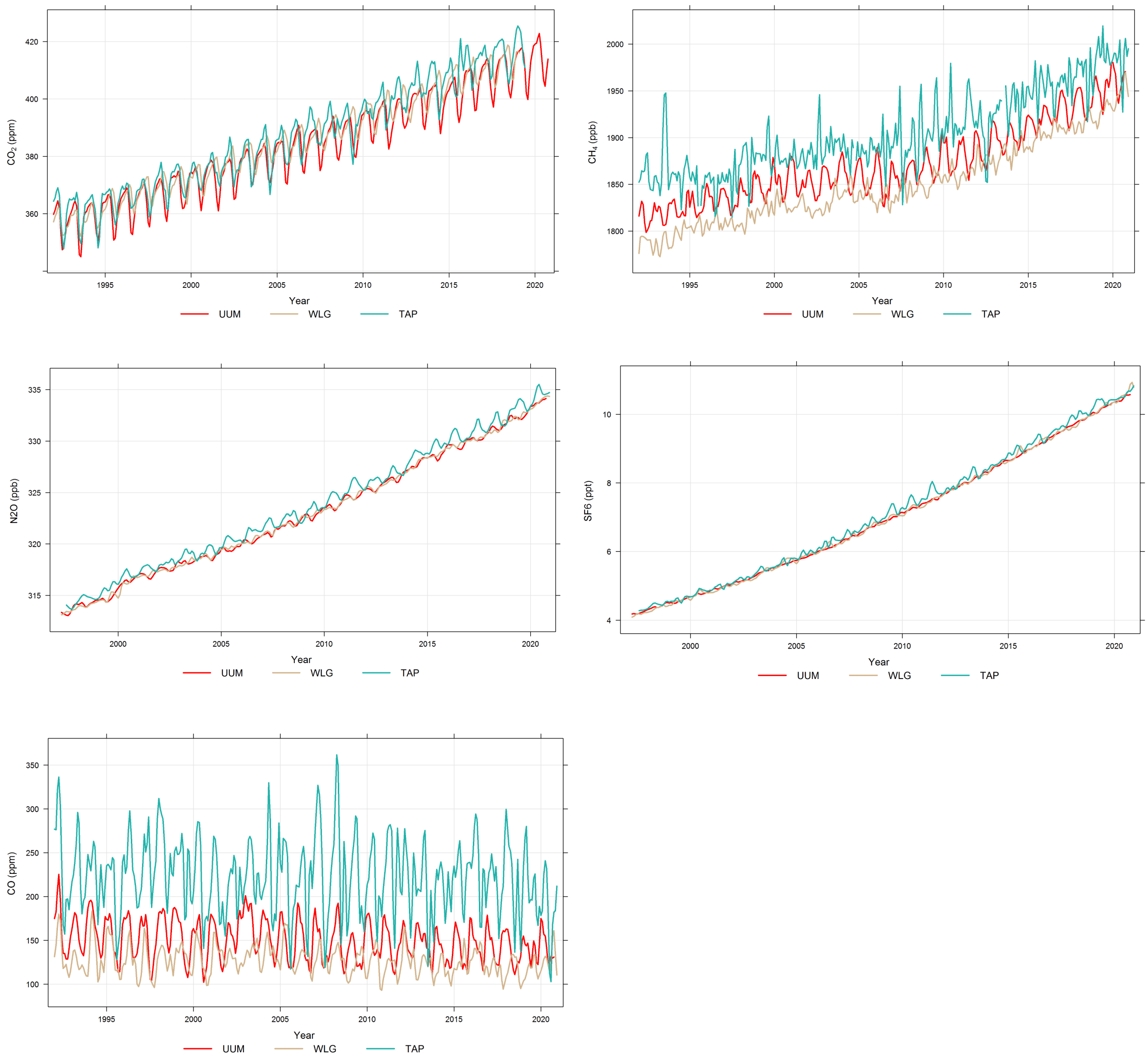

Figure 15. Time series of GHG measured at UUM, WLG and TAP stations in 1992-2020

Figure 15 depicts the time series of GHG measured at WLG, UUM, and TAP, and from 1992 to 2018. At all observation sites, CO_2 concentrations in the atmosphere tend to rise. From those values, CO_2 concentration is shown as the highest average value in TAP which was around 386.6 ppm, and also the maximum value of 425.2 ppm was observed there. Compared to the other two stations, the average value is higher than 0.7% and 0.5% in UUM and WLG respectively.

As for the CH_4, its concentrations tend to increase at all observation sites. Like CO_2, the highest average concentration of 1904.9 ppb was noted at TAP and the lowest value was recorded in WLG, which was 1.8% lower than TAP. Furthermore, according to the previous study, at each monitoring location in the East Asian region, different seasonal cycles are seen. While WLG is further inland on the continent, active ruminant emissions cause the atmospheric CH_4 level to rise slightly during the summer. UUM's seasonal variances are at their highest in December and lowest in June. Except for the WLG, atmospheric CH_4 concentrations are lowest in the summer and highest in the fall and winter in the East Asian region. The location of TAP, on the other hand, is heavily influenced by sources, as well as the influence of sinks induced by North Pacific air masses in summer, because its location is on downwind of China [30].

The next gases, concentrations of N_2O and SF_6 prohibit almost the same average at three stations – N_2O was 323 ppb, 323.8 ppb, and 323 ppb and SF_6 was 7 ppt, 7.2 ppt, and 7 ppt at UUM, TAP, and WLG stations, respectively. Even though CO concentration was very different at those stations. The average concentration of CO at WLG was 127.4 ppm. At UUM it was 17.7% higher and even at TAP, it was 74.3% higher. Pollutants emitted on a massive scale from the East Asian continent, mainly from China, are known to have an impact on Korea, with some traveling hundreds, if not thousands, of kilometers away.

4.3. Climate radiative forcing

Radiation forcing includes many parameters such as solar radiation, albedo, surface changes, water vapor, and stratospheric ozone. To calculate the long-term radiation forcing of anthropogenic GHGs in Mongolia, data from the Ulaan-Uul station is used. Figure 16 shows the time series of radiation forcing calculated from the measured values of greenhouse gases (CO_2, CH_4, N_2O, SF_6) at the Ulaan-Uul station using the expression in Table 1. It illustrates which of the anthropogenic greenhouse gases is more effective and dominant in climate change. Since the start of greenhouse gas measurements, the CO_2 radiation forcing has increased from 1.3 W/m^2 to 2.1 W/m^2 (61.9%), CH4 from 0.51 W/m^2 to 0.56 W/m^2 (9.8%), and N2O from 0.14 W/m^2 to 0.19 W/m^2 (35.7%), and the SF6 gas radiation load increased from 0.0027 W/m^2 to 0.01 W/m^2 (270.4%), respectively. Between 1998 and 2020, the global average radiative forcing of greenhouse gases increased by 32.3% (0.78 W/m^2) [31], while in Mongolia it increased by 31.9%. On average, CO_2 accounts for about 62.9% (~0.7 W/m^2) of anthropogenic GHG radiative forcing worldwide, making it the largest contributor to climate change since the 1990s.

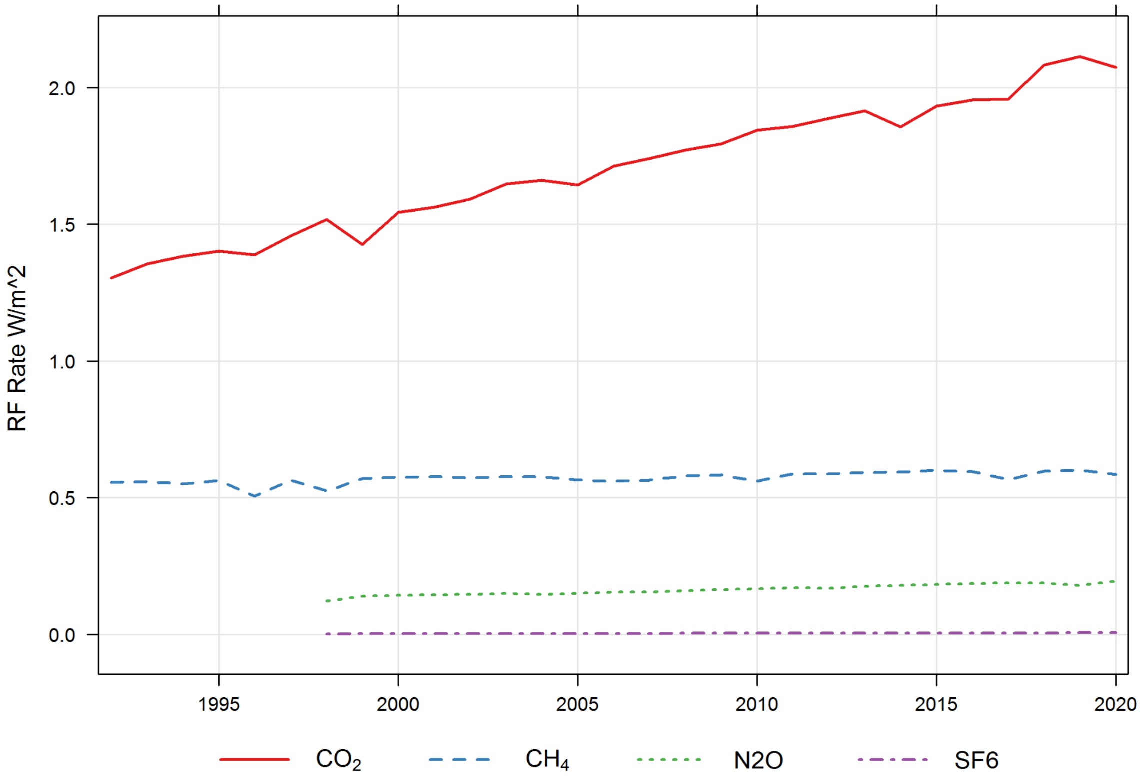

Figure 16. Time series of radiative forcing based on measured GHG at Ulaan-Uul station for 1992-2020

Likewise, CO_2 is also a major contributor to radiative forcing in Mongolia – 73.4% of anthropogenic radiative forcing is CO_2, 19.6% is CH_4, 6.64% is N_2O, and 0.35% is SF_6 (Figure 17). The increase in SF_6 gas content and radiative forcing is relatively high compared to those of other gases due to its high global warming potential. To note, to estimate the climate radiative forcing, GHGs measured at the Ulaan-Uul station are considered in this study, but other factors such as aerosols, ozone, solar irradiation, etc. are not taken into account. Thus, an extended study is recommended.

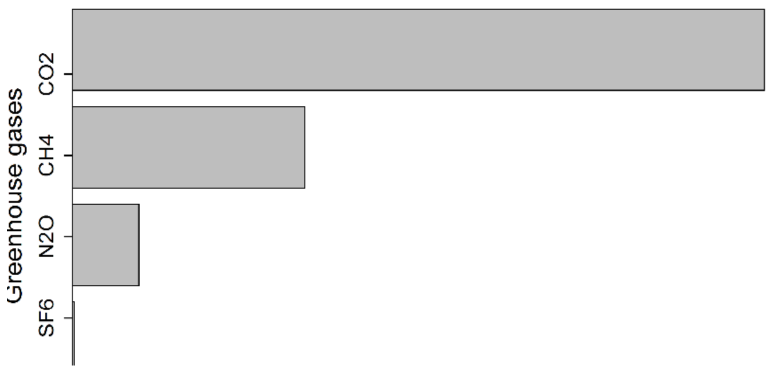

Figure 17. Radiative forcing caused by major GHG in Mongolia for 1992-2020

4.4. Forecast of greenhouse gases

Figure 18 shows the forecasts of GHG concentrations in the Gobi region of Mongolia until 2033 using the previously observed monthly mean data of the Ulaan-Uul station measured between 1992 and 2020 and the ARIMA model.

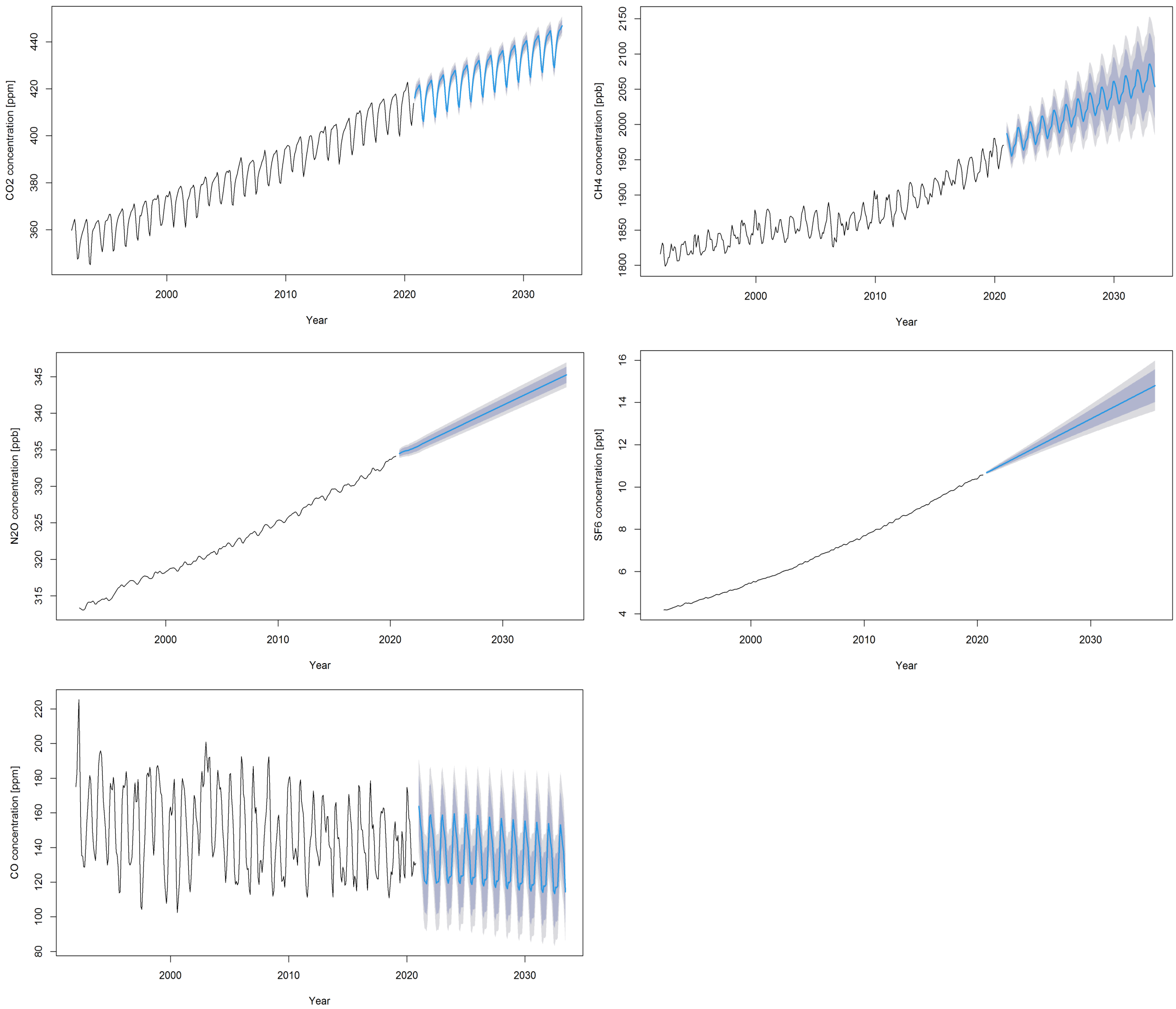

Figure 18. Forecasts of concentrations of GHG until 2033

The calculations were performed using the ARIMA model, a widely used statistical method for predicting time series. In predicting future changes based on long-term measured values, the regression (autoregression) of its previous values, the moving average, and the trend are maintained. It is written as ARIMA (p, d, q), where p denotes the order of the autoregressive model, d denotes the degree of differencing, and q denotes the order of the moving-average model, use differencing to turn a non-stationary time series into a stationary one, then use historical data to forecast future values. To forecast future values, these models use "auto" correlations and moving averages over residual errors in the data. Thus, the advantage of using ARIMA models to generalize the forecast, all that is required is prior data from a time series and predict short-term forecasts well.

Assuming that the GHG emission reduction measures remain at the same level as before, the growth trend of GHG emissions will continue and by 2033, the GHG concentrations in Mongolia are likely to increase as follows:

- CO_2 is likely to reach around 463.6 ppm by 2033, which is 12.1% higher than the current average concentration. According to the UN Climate Change synthesis report, global emissions will grow 16% by 2030 compared to 2010 levels under government policies put up since the beginning of 2020. This puts the globe dangerously off course to accomplishing the 45% reduction in greenhouse gas emissions that climate experts think is required to meet the Paris Agreement's aim of keeping global warming to 1.5°C [32].
- CH_4 is forecasted to be around 2085.9 ppb by 2033, or 6.2% higher than the average concentration of 2020. Likewise, by 2030, global anthropogenic methane emissions are expected to rise by about 9% over 2020 levels, reaching 10,220 million metric tons of CO_2 equivalents (Figure 19) [33] according to the source of global CH_4.

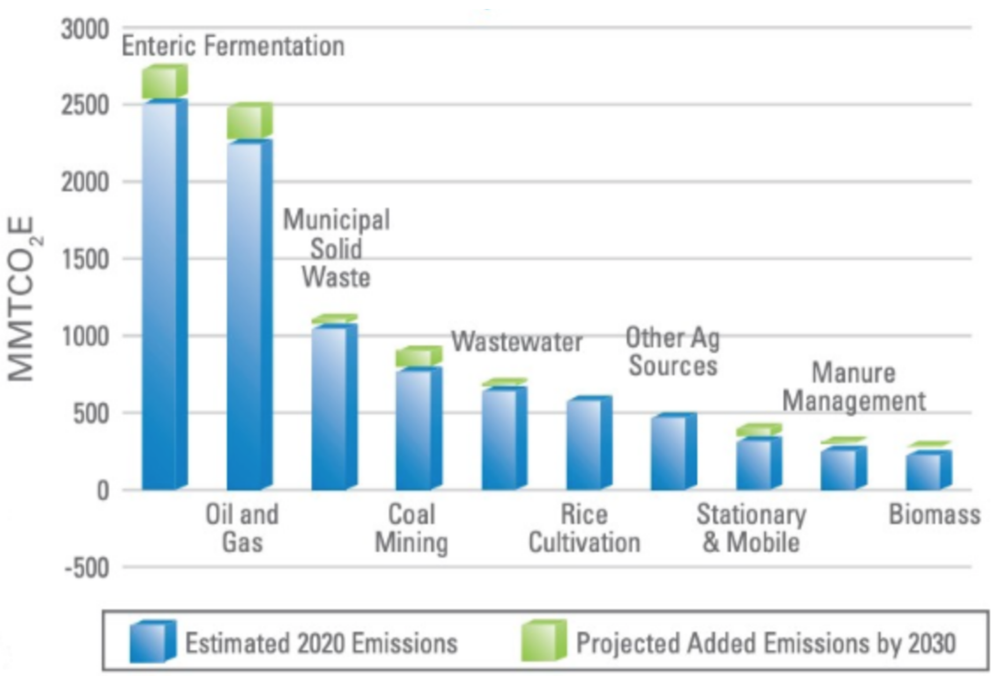

Figure 19. Estimated and projected global anthropogenic methane emissions by source, 2020 and 2030

- N_2O is likely to be around 345.3 ppb by 2033, or 3.5% higher than the concentration of 2020.

- SF_6 is likely to reach around 14.8 ppt by 2033, or 41% higher than the concentration of 2020. In comparison to the other studies, this gas has a lifetime in the atmosphere of over 1,000 years, and its installed base is predicted to rise by 75% by 2030 globally [34].
- A slight increase in CO concentration of 3% is forecasted. It is likely to be around 114.3 ppm by 2023.

Overall, all the GHG concentrations are expected to rise and if it is continued in the future, emissions will exacerbate climate change.

The results of this subchapter are published in the scientific journal "The Environment" which is run by the Mongolian Association of Environmental Engineers (See Appendix 3).

4.5. Relationship between carbon dioxide and temperature

The relationship between temperature and greenhouse gases is well studied. John Tyndall, a scientist, observed Earth's natural greenhouse effect in the 1860s and proposed that tiny changes in air composition may cause climate variations. Svante Arrhenius, a Swedish physicist, predicted that changes in atmospheric carbon dioxide levels might significantly influence surface temperature through the greenhouse effect in a fundamental study published in 1896. After that, Guy Callendar linked rising carbon dioxide levels in the atmosphere to global warming in 1938. Since then, a relationship between CO_2 and temperature has been studied. According to the IPCC AR4 [35], the observed increase in global average temperature is most certainly related to rising greenhouse gas (especially CO_2 concentrations. The physical foundations for this claim are as follows:

1. Radiative forcing is increasing from increased CO_2 concentrations, and it should increase atmospheric temperature.
2. Atmospheric CO_2 concentrations have been increasing over the past century, and thus a significant increase in atmospheric temperature should be expected.

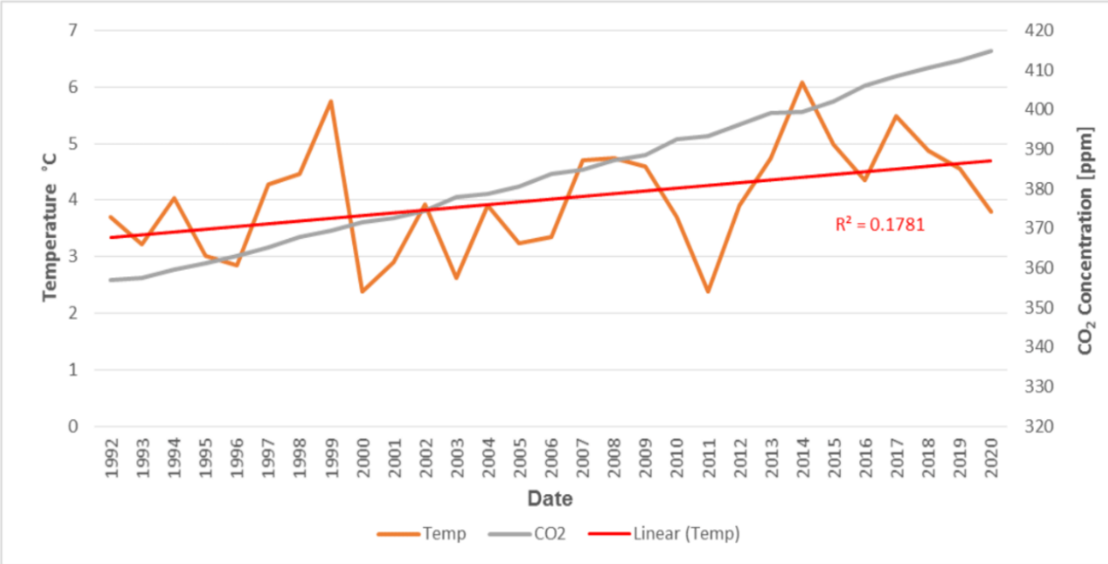

Figure 20. Changes in atmospheric CO_2 and temperature of Erdene soum

In Figure 20, CO_2 concentration, the temperature at Erdene soum of Dornogovi aimag, and its trend from 1992 to 2020 are shown. As it was mentioned previously, CO_2 concentration has been increasing noticeably. The temperature has been fluctuating during these years and the rising trend in temperature is seen. In the 1990s, the average temperature was 3.9°C and last 20 years, it became 4.1°C. In total, during the last 29 years, Erdene soum's temperature had increased by 4.6%.

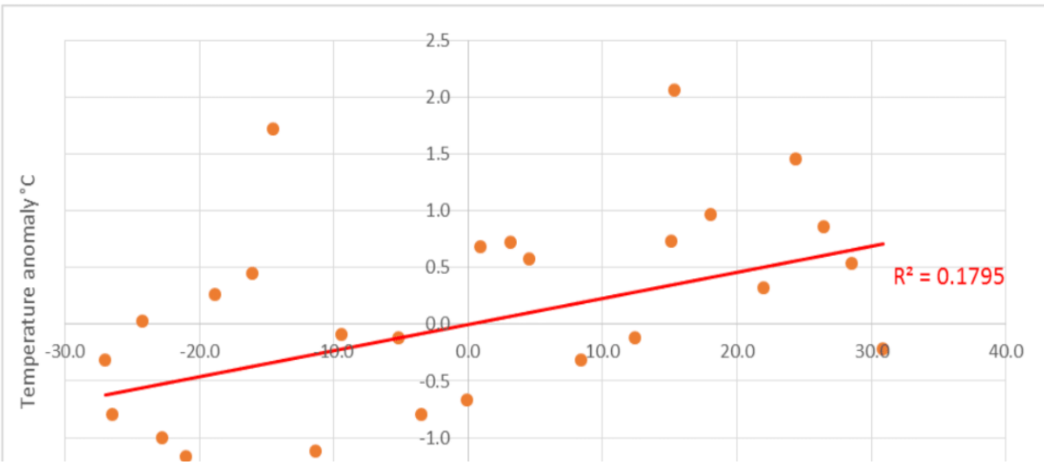

Figure 21. The relationship between annual change in CO_2 concentration and average annual temperature of Erdene soum

After calculating the CO_2 anomaly, the relationship between CO_2 anomaly and temperature anomaly can be shown (figure 21). A weak and positive relationship is found with a correlation coefficient of 0.1795. Even though it has hard to tell whether they have a strong correlation because the data used in this calculation is 29 years only. It is recommended to observe the change using long-term data.

Furthermore, in Table 5, correlation coefficients between GHGs and temperature are calculated. It is seen that correlation of CO_2 is the highest among GHGs. The IPCC asserted that rising atmospheric quantities of greenhouse gases (particularly CO_2) are the primary force behind climate change [36]. All of these findings highlight the complexity of the Earth's climate system, whose mechanisms cannot be traced to a single element like CO_2 levels. A short-term temperature change is usually impacted more by other causes. For example, Lean and Rind claimed that 10-year accumulated cooling effects from natural causes like solar radiation and volcanic eruptions might cancel out some of the warming effects from greenhouse gases [37].

Table 5. Correlation coefficients of GHG and mean temperature of Erdene soum since 1992

	CO_2	CH_4	N_2O	SF_6	CO
Correlation coefficient	0.4237	0.4116	0.1082	–0.0646	–0.3873

All in all, human activities and natural forces both contribute to climate change, but quantifying their proportional contributions is difficult. The global climate system is influenced by both anthropogenic and natural influences. Natural factors such as solar activity and volcanic eruptions alter solar radiation, atmospheric and oceanic circulations, and atmospheric components, whereas human activities, particularly fossil fuel combustion and deforestation, cause emissions of greenhouse gases such as CO_2 and CH_4.

5. Discussion and Conclusion

With the importance of greenhouse gas effects on the environment and increased interest in it, the greenhouse gases have been studied and systematically measured around the world since 1859, and it has been continuously sampling and got processing the results in Mongolia since 1992. Overall, using the 29-year measurement data, basic research on a variety of topics, including GHG general characteristics, climate radiative forcing, and temperature relevance are scrutinized. A number of analyses were done, including time series, seasonal fluctuations, future projections, and temperature relationships.

During those years, the concentrations of CO_2, CH_4, N_2O, and SF_6 were measured in remote Gobi regions of Mongolia and these long-lived GHGs have been steadily increasing and related to that, the temperature has been increasing as well. Their concentrations increased from 6.6% to 150% during the last 29 years and the growth rate per year was around 0.3%-4.1%. However, CO concentration decreased by 4.9%. As for the characteristics of GHGs, they are tended to rise during winter and decline during summer. The reason is in the winter, fossil fuel, and biomass combustion significantly increase emissions and contribute to greater mole fractions in the atmosphere. Furthermore, due to the higher photosynthesis process, GHG concentrations in the atmosphere are lowest in the summer months. Importantly, even though we do not have big factories, industries, or farming like other cities, GHG concentrations are similarly close to the compared cities, the concentration of Mongolian mean concentrations are just less than 0.07%-1% of the world average.

Secondly, the important thing is that the radiative forcing rises with an increase in GHGs. In Mongolia, CO_2 (73.4%) constitutes the majority of radiative forcing from human activities. For other gases, the order of importance is CH_4 (19.6%), N_2O (6.64%), and SF_6 (0.35%). Although the percentage of radiative forcing is small, the SF6 gas content is increasing the fastest. This high radiative forcing can cause climate sensitivity such as fluctuating between states of overall warming and cooling, which means it is one of the factors of climate change. In general, these results are in agreement with results found in other parts of the world.

Thirdly, the relationship between CO_2 and temperature is studied and the coefficients of correlation between GHGs and temperature are calculated. Erdene soum's temperature has risen by 4.6% in the last 29 years. Also, CO_2 has the strongest correlation among GHGs, with a value of 0.4237. Climate change is caused by both human activity and natural causes, but measuring their proportionate contributions is difficult.

Lastly, it is important to anticipate future situations when planning future adaptation and mitigation measures. The study estimates that changes in GHGs concentration levels, a major contributor to the climate, will continue until 2033, with growth expected to continue from 3% to 12.1%

compared to the current average value. The computations were done with the ARIMA model, which is a popular statistical tool for forecasting time series.

The results of this bachelor thesis are introduced in the students' scientific conference "Environmental engineering-2022" (See Appendix 4).

5.1. Further recommendations

Many greenhouse gases persist for lengthy periods in the atmosphere. As a result, even if emissions ceased to rise, global greenhouse gas concentrations would continue to rise for hundreds of years. There are several concerns would be suggested regarding the thesis topic:

- On the research:
    - In the case of big land Mongolia, establish greenhouse gas monitoring stations at points other than Ulaan-Uul
    - Expand greenhouse gas and climate change research, especially in provinces
    - Detailed study of the spatial characteristics of greenhouse gases using remote sensing data
    - Study the vertical distribution of greenhouse gases
    - Create a database of greenhouse gas concentration and make it available for open use
- On the policy and operational activities:
    - Use the results of calculations, research, and measurements as evidence for climate change mitigation and adaptation
    - Plan and implement policies and activities tailored to the specifics of Mongolia based on evidence.

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7. Appendix

Appendix 1. Summary plot of GHG (CO_2, CH_4, N_2O, SF_6, and CO) measured at Ulaan-Uul station in 1992-2020

Монгол орны хүлэмжийн хийн агууламжийн харьцуулсан судалгааны дүнгээс

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Хүлэмжийн гэж нэрлэгдэх хийнүүдийн агууламж агаар мандалд нэмэгдсэнээр газрын гадаргаас цацрах урт долгионт цацрагийг барьж тропосферийн температурыг нэмэгдүүлэх нөлөө үзүүлдэг. Дэлхийн дунджаар нүүрстөрөгчийн давхар ислийн агууламж аж үйлдвэржилтээс өмнөх үетэй харьцуулахад 50%-иар нэмэгдсэн. Энэхүү судалгаанд NOAA Global Monitoring Laboratory-ийн Монгол орны нутаг дэвсгэр дээрх хүлэмжийн хийн шинжилгээний Улаан-Уул өртөөний 1992-2020 оны мэдээг ашиглан хүлэмжийн хийн өөрчлөлт, хандлага, цаг хугацааны анализ хийн дэлхийн дундаж болон ажиглалтын бусад цэгүүдийнхтэй харьцуулав. CO2 агууламж 16.7%, CH4 агууламж 2.7%, N2O агууламж 2.9%, SF6 хийн агууламж 128.4%-иар тасралтгүй өссөн байна. Харин CO агууламж 7.0%-иар буурсан байна.

Түлхүүр үгс: хүлэмжийн хий, хүлэмжийн хийн өөрчлөлт, Монгол Улаан-Уул, статистик боловсруулалт

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Appendix 3. Article submitted to the journal "The Environment" which is run by the Mongolian Association of Environmental Engineers

STUDY ON ROLE OF SOME LONG-LIVED GREENHOUSE GASES IN CLIMATE FORCING IN MONGOLIA FOR 1992 TO 2020

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Abstract

Over the past few decades, the world's climate has been dramatically changing due to anthropogenically-induced greenhouse gases. Those greenhouse gases differently affect the climate, and this study examines the changes in concentrations of long-lived greenhouse gases measured in Mongolia since 1992, predictions until 2030, and radiative forcing, which is one of the indicators of climate change. CO_2, CH_4, N_2O, and SF_6 concentrations have been continuously increasing. By 2030, CO_2 concentration in Mongolia is predicted to increase to 463.6 ppm or 12.1% compared to the current level. In Mongolia, 73.4% of the climate radiative forcing is CO_2, 19.6% is CH_4, 6.64% is N_2O, and 0.35% is SF_6.

Keywords: greenhouse gas, long-lived greenhouse gases, radiative forcing, Mongolia

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МОНГОЛ ОРНЫ АГААР МАНДАЛ ДАХЬ ХҮЛЭМЖИЙН ХИЙНҮҮДИЙН (1992-2020 ОН) УУР АМЬСГАЛД ҮЗҮҮЛСЭН НӨЛӨӨЛЛИЙН СУДАЛГАА

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Хураангуй

Сүүлийн жилүүдэд хүний үйл ажиллагаанаас үүдэлтэй хүлэмжийн хийн нөлөөгөөр дэлхийн уур амьсгал огцом өөрчлөгдөж байна. Хүний үйл ажиллагаанаас үүдэлтэй хүлэмжийн хийнүүдийн цацрагийн нөлөөлөл ялгаатай байдаг бөгөөд энэхүү өгүүлэлд Монгол орны нутаг дэвсгэрт 1992 оноос хойш хэмжигдсэн зарим хүлэмжийн хийнүүдийн өнөөгийн болон 2030 он хүртэлх ирээдүйн өөрчлөлт, хүлэмжийн хийнүүдийн уур амьсгалын өөрчлөлтөд нөлөөлөх нэг үзүүлэлт болох цацрагийн ачааллын өөрчлөлтийг судлав. CO_2, CH_4, N_2O, SF_6 хийн агууламж тасралтгүй нэмэгдсэн байна. 2030 он гэхэд Монгол орны хэмжээнд CO_2 хийн агууламж 463.6 ppm буюу одоогийн дундаж утгаас 12.1%-иар өсөхөөр байна. Монгол орны хувьд хүний үйл ажиллагаанаас үүдэлтэй цацрагийн ачааллын 73.4%-ийг CO_2, 19.6%-ийг CH_4, 6.64%-ийг N_2O, 0.35%-ийг SF_6 эзэлж байна.

Түлхүүр үгс: хүлэмжийн хий, агаар мандалд удаан оршдог хүлэмжийн хий, цацрагийн ачаалал, Монгол

Оршил

Агаар мандлын найрлагын 99.9%-ийг азот, хүчилтөрөгч, аргон хий эзлэх ба үлдсэн ул мөрийн төдий хэмжээгээр агуулагдаж байгаа зарим хийнүүд дэлхийн агаар мандын цацрагийн тэнцэлд чухал үүрэг гүйцэтгэж байдаг. Нарнаас ирж буй богино долгионт цацрагийг дэлхийн гадарга шингээж, түүнийгээ урт долгионт цацраг хэлбэрээр агаар мандал руу буцаан цацруулдаг бөгөөд үүний нөлөөгөөр агаар мандлын тропосферийн үе давхаргад нэмэлт дулаарал бий болохыг "хүлэмжийн үзэгдэл" гэдэг. Хүлэмжийн хийд нүүрстөрөгчийн давхар исэл (CO_2), метан (CH_4), азотлог исэл (N_2O) зэрэг хийнүүд орно.
Нүүрстөрөгчийн давхар ислийн дэлхийн дундаж агууламж 1750-1800 оны дунджаас бараг 50%-иар нэмэгджээ [1]. 1850-1900 оноос хойшхи хүлэмжийн хийн агууламжийн өсөлтөд хүний үйл ажиллагаа гол нөлөөлөгч хүчин зүйл болж байгаа ба хүлэмжийн хийн огцом өсөлт дэлхийн гадаргын дундаж температур 1.09°C-аар нэмэгдүүлжээ [2]. Энэхүү дулааны хуримтлал нь дэлхийн болон бүс нутгийн уур амьсгал, цаг агаарын нөхцөл байдлыг өөрчилж, дэлхийн дулаарлыг үүсгэх гол хүчин зүйл болж байна. Монгол орны хувьд 1940-2020 оны хооронд агаарын жилийн дундаж температур 2.25°C-аар нэмэгдсэн [3]. Хүйтний улиралд дулаарал илүү тод ажиглагдаж, өвлийн улиралд дунджаар 3.6°C, хавар, намрын улиралд 1.4-1.9°C-аар нэмэгджээ. Хэрэв агаар мандал дахь хүлэмжийн хийнүүдийн агууламж өссөн хэвээр байвал дэлхийн дундаж температурын өсөлт нь 2100 он гэхэд 1.5°C-аас 2.4°C-ийн хооронд нэмэгдэх төлөвтэй байгаа бөгөөд хүлэмжийн хийн ялгарлыг бууруулах хамгийн ашигтай хувилбараас бусад бүх хувилбарт хамгийн багадаа 1.5°C-ээр нэмэгдэхээр байна [4].

Үүнээс гадна хүлэмжийн хийн өсөлттэй зэрэгцэн цацрагийн ачаалал ч мөн нэмэгдсээр байгаа юм. Цацрагийн ачаалал нь уур амьсгалын өөрчлөлтөд хувь нэмэр оруулах байгалийн болон хүний хүчин зүйл (жишээлбэл, хүлэмжийн хий, үүл, гадаргын альбедо зэрэг) өөрчлөгдсөний үр дүнд агаар

МОНГОЛ ОРНЫ ГОВИЙН БҮС НУТГИЙН ХҮЛЭМЖИЙН ХИЙН ОЛОН ЖИЛИЙН ЯВЦ, ЦААШДЫН ХАНДЛАГА, ДУЛААРАЛД ҮЗҮҮЛЭХ НӨЛӨӨ

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Хураангуй

Сүүлийн хэдэн арван жилийн турш хүний үйл ажиллагаанаас үүдэлтэй хүлэмжийн хийн ихсэж, үүний улмаас дэлхийн уур амьсгал эрс өөрчлөгдөж байна. CO_2, CH_4, N_2O болон SF_6-ийн агууламж тасралтгүй нэмэгдсээр байгаа ба энэхүү судалгаанд 29 жилийн хэмжилтийг ашиглан хүлэмжийн хийн ерөнхий шинж чанар, температурын хамаарал зэрэг хэд хэдэн асуудлыг хамарсан суурь судалгааг хийсэн. Монгол орны говийн алслагдсан бүс нутгуудад CO2, CH_4, N_2O, SF_6-ийн агууламжийг хэмжиж байсан бөгөөд сүүлийн 29 жилийн хугацаанд 6.6%-аас 150% болж өссөн ба жилийн өсөлтийн хурд 0.3%-4.1% орчим байв. Харин CO-ийн агууламж 4.9%-иар буурсан байна.

Мөн түүнчлэн хүлэмжийн хий нэмэгдэхийн хэрээр цацрагийн нөлөөлөл нэмэгдсээр байна. Манай улсад хүний үйл ажиллагаанаас үүдэлтэй цацрагийн нөлөөллийн дийлэнх хувийг CO_2 (73.4%) эзэлдэг. Бусад хийн хувьд CH_4 (19.6%), N_2O (6.64%), SF_6 (0.35%) байна. Хэдийгээр цацраг идэвхт хүчний хувь хэмжээ бага боловч SF_6 хийн агууламж хамгийн хурдан нэмэгдэж байна.

CO_2 ба температурын хамаарлыг судалж, хүлэмжийн хий ба температурын хамаарлын коэффициентийг мөн энэхүү ажилд тооцоолсон. Эрдэнэ сумын агаарын температур сүүлийн 29 жилд 4,6 хувиар нэмэгдсэн байна. Мөн CO_2 нь хүлэмжийн хийнүүдийн дунд хамгийн хүчтэй хамааралтай бөгөөд 0.4237 гэсэн утгатай. Эцэст нь ирээдүйд дасан зохицох, бууруулах арга хэмжээг төлөвлөхдөө ирээдүйн нөхцөл байдлыг урьдчилан харах хэрэгтэй ба судалгаагаар уур амьсгалд гол нөлөө үзүүлж буй хүлэмжийн хийн агууламжийн түвшний өөрчлөлт 2033 он хүртэл үргэлжлэх бөгөөд одоогийн дундаж үзүүлэлттэй харьцуулахад 3%-иас 12.1% хүртэл өсөх төлөвтэй байна.

Түлхүүр үг: хүлэмжийн хий, уур амьсгалын өөрчлөлт, дэлхийн дулаарал, цацрагийн хүч, Монгол