ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DETERMINATION OF THE CARBON EMISSIONS OF ANTARCTIC EXPEDITIONARY RESEARCH VESSELS

M.Sc. THESIS

Efecan ÖZCAN

Department of Maritime Transportation Engineering

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ANTARKTİK SEFER ARAŞTIRMA GEMİLERİNİN KARBON EMİSYONLARININ BELİRLENMESİ

YÜKSEK LİSANS TEZİ

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Efecan Özcan, a M.Sc. student of ITU Graduate School student ID 512191018, successfully defended the thesis entitled "DETERMINATION OF THE CARBON EMISSIONS OF ANTARCTIC EXPEDITIONARY RESEARCH VESSELS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my mother,

FOREWORD

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May 2022

Efecan ÖZCAN
(Oceangoing Chief Officer)

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ABBREVIATIONS

AARI	: Arctic and Antarctic Research Institute
AIS	: Automatic Identification System
ASPA	: Antarctic Specially Protected Areas
BC	: Black Carbon
CH_4	: Methane
CHP	: Combined Heat and Power
CO	: Carbon Monoxide
CO_2	: Carbon Dioxide
COMNAP	: Council of Managers of National Antarctic Programs
ECA	: Emission Control Area
EEA	: European Environment Agency
EEOI	: Energy Efficiency Operational Index
EF	: Emission Factor
EGR	: Exhaust Gas Recirculation System
EMEP	: European Monitoring and Evaluation Programme
EU	: European Union
GHG	: Greenhouse Gases
HC	: Unburned Hydrocarbon
HFO	: Heavy Fuel Oil
HP	: Horse Power
IAATO	: International Association of Antarctica Tour Operators
ICAO	: International Civil Aviation Organization
IMO	: International Maritime Organization
IPCC	: Intergovernmental Panel on Climate Change
kW	: Kilowatt
kWh	: Kilowatt per hour
LNG	: Liquefied Natural Gas
LTO	: Landing and Take-Off Operations
MDO	: Marine Diesel Oil
MEPC	: Marine Environment Protection Committee

N_2O : Nitrous Oxide
NASA : National Aeronautics and Space Administration
NH_3 : Ammonia
NMVOC : Non-Methane Volatile Organic Compound
NO_2 : Nitrogen Dioxide
NOAA : National Oceanic and Atmospheric Administration
NOx : Nitrogen Oxides
PM_{10} : Particulate Matter up to 10 micrometers in size
$PM_{2.5}$: Particulate Matter up to 2.5 micrometers in size
RPM : Revolutions per Minute
SCAR : Scientific Committee on Antarctic Research
SCR : Selective Catalytic Reduction
SFOC : Specific Fuel Oil Consumption
SHP : Shaft Horse Power
SO_2 : Sulphur Dioxide
SOx : Sulphur Oxides
TEU : Twenty-Foot Equivalent Unit
TSP : Total Suspended Particles
UV : Ultraviolet
WMO : World Meteorological Organization

SYMBOLS

C_f	: Fuel consumption
C_h	: Fuel consumption per hour
h	: Hours
L	: Engine load
m_{co2}	: The mass of emitted CO_2
m_{pg}	: The mass of emitted pollutant gas
P	: Engine power
Q_c	: The heat released as a result of combustion
t	: Days

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DETERMINATION OF THE CARBON EMISSIONS OF ANTARCTIC EXPEDITIONARY RESEARCH VESSELS

SUMMARY

The vast majority of studies carried out in Antarctica are provided by research vessels. However, data on the environmental impact of carbon emissions from research vessels are limited. In this study, it is aimed to develop two different scenarios with statistical methods, to determine the emissions of ships conducting scientific expeditions in Antarctica and to propose different methods to reduce the emissions. After calculating the fuel consumption of the research ship and aircraft according to these scenarios, the emission amounts of pollutant gases were estimated for each scenario using the emission factors in the Atmospheric Emission Inventory Guidebook of European Monitoring and Evaluation Program / European Environment Agency (EMEP/EEA) and carbon emission factors in resolution 212(63) of International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC). In the first scenario, emissions were calculated assuming that scientific expeditions were only made by sea from Europe to the West the Antarctic Peninsula. In the second scenario, the calculation is made by assuming that the same region is used in an integrated way by air and sea transportation. A total of 2143 tons of CO_2 emissions were calculated in the first scenario where only the sea route is used. The carbon emissions due to open sea voyage, staying at anchor and ice navigation were calculated as 60%, 38% and 2%, respectively. In the second scenario, where the expedition is integrated with the airline, 1218 tons of CO_2 emissions were calculated, the emission due to staying at anchor, flight, open sea voyage and ice navigation were found as 66%, 21%, 10% and 3% of, respectively. The calculations showed that the use of a research vessel along with the airline can reduce emissions by 57% in this study. In conclusion, this study shows that the effects of carbon emissions on the Antarctic environment can be reduced if countries that are not geographically close to Antarctica use air and sea transportation together, instead of sending research vessels directly for Antarctic expeditions.

ANTARKTİKA’DAKİ ARAŞTIRMA GEMİLERİNİN KARBON EMİSYONLARININ BELİRLENMESİ

ÖZET

İklim değişikliğinin neden olduğu küresel ısınma nedeniyle kutup bölgelerindeki buzulların erimesi birçok çevre sorununa yol açmaktadır. İklim araştırmalarını güçlendirmek ve Dünya'yı daha iyi anlamak için bilim insanları kutup bölgelerinde araştırmalar yürütmektedir. Özellikle Antarktika'daki araştırmalar, iklim değişikliğini anlamak ve önlem almak için çok önemlidir. Antarktika, yeryüzünde yerli nüfusun bulunmadığı tek kıtadır. 20. yüzyıla kadar hiçbir insan faaliyetinin olmaması, burada elde edilen verilerin antropojenik kirliliğin belirlenmesinde referans değer olarak kabul edilmesini sağlamaktadır. 1991'de Madrid'de imzalanan ve 1998'de yürürlüğe giren Antarktika Antlaşması'ndaki Çevre Koruma Protokolü, Antarktika'yı Antarktika çevresinin korunması için barış ve bilim için doğal bir rezerv olarak belirtir.

Kutup bölgelerinde lojistik, bu bölgenin anakaradan uzak olması ve iklim koşullarının çok sert olması nedeniyle oldukça zordur. Tüm bunlar göz önüne alındığında Antarktika yaz mevsimi genellikle seferlerin, ikmal operasyonlarının ve geçici işlerin planlandığı dönemdir. Bu seferler ve operasyonlar sırasında ulaşım genellikle hava ve deniz yoluyla veya bunların iç içe geçtiği bir kombine ulaşım modeliyle gerçekleşmektedir. 1959'da Antarktika Antlaşması'nın imzalanmasından sonra, Antarktika tamamen bilim insanlarına ayrılmış bir kıta haline geldi. Yarım asırdan uzun bir süredir bölgede faaliyet gösteren birçok ülkenin araştırmalarına destek olan araştırma istasyonları ve sezonluk istasyonlar bilimsel faaliyetlerine günümüzde de devam etmektedir. Bölgeye sefer yapan araştırma gemileri, Güney Okyanusunda ve Antarktika kıyılarındaki faaliyetleriyle karbon emisyonlarını arttırmaktadır.

Antarktika seferlerinden kaynaklanan emisyonları tahmin etmek için iki senaryo hazırlanmıştır. İlk senaryoda, Antarktika seferi yalnızca Avrupa'dan Antarktika'ya bir araştırma gemisi kullanılarak gerçekleştirilir. İkinci senaryoda, Antarktika seferi, Avrupa'dan Şili'ye hava yoluyla ulaşılarak ve ardından araştırma gemisine binilerek gerçekleştirilir. Her iki senaryoda da aynı gemiler kullanılır ve aynı bölgede eşit sürelerde araştırma yapılır. Karbon emisyonlarının tespit edilmesi için Uluslararası Denizcilik Örgütü (IMO) ve Avrupa İzleme ve Değerlendirme Programı / Avrupa Çevre Ajansı (EMEP/EEA) emisyon faktör envanterlerinde yer alan yakıtların karbon emisyon faktörleri kullanılmıştır. Emisyon miktarı hesaplanırken istatistiksel yöntemden faydalanılmıştır.

Senaryoların aşamaları harflerle kodlanarak emisyon hesaplarını kolaylaştırması hedeflenmiştir. İlk senaryoda, A harfli kod, Avrupa'dan Antarktika'ya açık deniz seyrini, B harfli kod Antarktika kıyılarında buzul seyri, C harfli kod ise 30 gün boyunca demirde veya driftte araştırma yapılan safha anlamlarında kullanılmıştır. İkinci senaryoda ise, D harfli kod Avrupa'dan Şili'ye uçuşu, E harfli kod Şili'den Antarktika'ya açık deniz yolculuğu anlamlarına gelecek şekilde kodlanmıştır. B ve C kodları ilk senaryo ile aynı anlamdaki kodlama olarak hesaba katılmıştır. Dolayısıyla,

ilk senaryo için toplam emisyon, A, B ve C kodlarının toplamı ve ikinci senaryo için toplam emisyon, D, E, B ve C kodlarının toplamı olarak emisyonlar belirlenmiştir.

Senaryolardaki emisyonlar her aşama için ayrı ayrı hesaplanmış ve birbirleriyle karşılaştırılmıştır. Senaryolar, fazlarına göre karbondioksit ve diğer gazlar olarak kategorize edilerek değerlendirilmiştir. İlk senaryoda 2143 ton CO_2 salınırken, ikinci senaryoda bu değer 1218 ton olarak hesaplanmıştır. Diğer sera gazları ilk senaryoda 54 ton salınırken, ikinci senaryoda yalnızca 26 ton olarak hesaplanmıştır. Bu nedenle, ikinci senaryo en çevre dostu Antarktik seferi olarak tespit edilmiştir. Bu senaryoda hem karbon hem de azot türevli gazlar en aza indirilmiştir.

Karbon emisyonlarını azaltmanın temel prensibi yakıt tüketimini azaltmaktır. Fosil yakıtlar ne kadar az tüketilirse, o kadar az karbondioksit üretilir. Rota optimizasyonu ile mesafeler ve seyahat süreleri kısaltılabilirse karbon emisyonlarında azalma olacaktır. Örneğin Antarktika kıtasına yakın ülkelerden seferler başlatılırsa seyir mesafesi kısalacağı için yakıt tasarrufu sağlanacaktır. Bunun faydası, ikinci senaryoda havayolu entegrasyonunda elde edilen değerlerle gösterilmiştir.

Antarktika seferlerinde araştırma gemilerinin seyir süreleri arttıkça karbon salınımı da artmaktadır. Araştırma gemisi, seferin tüm aşamalarında kullanılan tek araç olduğundan, en fazla CO_2 emisyonu ilk senaryoda salınmıştır. İkinci senaryoda ise havayolu entegrasyonu ile emisyonlarda gözle görülür bir azalma olduğu belirlenmiştir. Bu bilgiler ışığında, birinci senaryoda seyir süresinin ikinci senaryoya göre çok daha uzun olması nedeniyle, emisyonların seferin lojistik kısmında daha çok olduğu ve en yüksek değere birinci senaryoda ulaşıldığı belirlenmiştir. En yüksek emisyon meydana gelen sefer aşamasının, yakıtın enerji ve ısınma ihtiyacı için kullanıldığı demirde ya da drift yaparak sahada beklendiği araştırma safhası olduğu belirlenmiştir.

Rota optimizasyonu ve ekonomik sürat uygulamarı ile yakıt ve salınım oranları dökme yük, konteyner ve tanker gemilerinde azaldığı literatürdeki çalışmalarda mevcuttur. Tezde üretilen senaryolar neticesinde yapılan hesaplamalar, Antarktika'ya sefer yapan araştırma gemileri için de benzer sonuç verdiğini göstermiştir. Aynı şekilde literatürde ticari gemilerin limanlarda ve iç sularda beklemelerinde meydana gelen çevre etkisi Antarktika'ya sefer yapan araştırma gemisi için senaryolarda yapılan hesaplamalarla karşılaştırıldığında benzer sonuca ulaşılmıştır. Tüm bu sonuçlar literatürdeki çalışmalarla uyuşmaktadır.

Antarktika seferlerinin çevre üzerindeki olumsuz etkilerini en aza indirmek için en temel yöntem yakıt tüketimini azaltmak olacaktır. Bunun için bölgesel koşullara ve bilimsel çalışmaların ihtiyaçlarına uygun olarak en az emisyona neden olan araştırma gemileri tercih edilmelidir. Ayrıca rota optimizasyonları ve düşük hızlı uygulamalarla emisyon oranlarında azalma sağlanabilir. Bölgenin soğuk iklimi göz önüne alındığında, araştırma safhasında ısıtma için gereken enerji de yakıt tüketimini artıracak bir faktör olarak görülmektedir. Sistemdeki baca gazları ile atılan atık ısıyı yeniden kullanabilen kojenerasyon teknolojileri, emisyonları ve yakıt tüketimini azaltabilecek yöntemler arasındadır.

Azot ve kükürt türevi gazların salınımını azaltmak için gemi makinesine ek filtreleme teknolojileri yerleştirilebilir. Alternatif yakıt kullanan gemiler azot ve kükürt emisyonlarını neredeyse sıfırlayacak ve karbon içeriği azalacağı için karbon emisyonlarını da önemli ölçüde azaltacaktır. Hibrit araştırma gemilerinin kullanımının Antarktika koşullarına dayanması sağlanabilirse, tüm emisyonlar büyük ölçüde sıfıra indirilebilir. Bu tezde belirtilmese de otonom gemiler Güney Okyanusu'ndaki tehlikeli bölgelerde uzaktan kumanda ile veri toplamak için kullanılabilir. Tez kapsamında hazırlanan senaryolarla yapılan hesaplamalar, Antarktika seferleri yapan araştırma gemilerine örnek teşkil etmektedir. Bu çalışmada elde edilen sonucun gelecekte bölgeye yapılacak yeni seferlerde farklı lojistik yöntemlerin uygulanmasını teşvik edeceği düşünülmektedir.

1. INTRODUCTION

The melting of the glaciers in the polar regions due to global warming caused by climate change leads to many environmental problems. In order to strengthen climate research and better understand the Earth, scientists are conducting research in the polar regions. Especially research in Antarctica is crucial for understanding and taking precautions against climate change. Antarctica is the only continent on Earth where no indigenous population exists. The fact that there was no human activity until the 20th century allows the data obtained here to be considered as a reference value for determining anthropogenic pollution.

The Protocol on Environmental Protection in the Antarctic Treaty, signed in Madrid in 1991 and entered into force in 1998, specifies Antarctica as a natural reserve for peace and science for the protection of the Antarctic environment. As an international agreement, it protects the environmental, scientific, historical and intrinsic (including wildlife and aesthetic) values of Antarctica. In environmental studies so far, scientists have documented the vulnerability of Antarctica and the Southern Ocean to human influences (Tin et al, 2009; Chown et al, 2012a; Chown et al, 2012b) and raised awareness of global environmental change. Scientists are gradually gaining a position to guide the policymakers for better protection of Antarctica and to keep it as pristine as it is. As a result of this, scientists are also enlightening the policymakers by conducting research on international environmental regulations. However, at this point, it is essential to provide both material and moral support from all authorities to the scientific community (Constable et al, 2014; Turner et al, 2014).

Logistics in the polar regions are very difficult due to the fact that this region is far from the mainland and the climatic conditions are very harsh (Tin et al, 2009). Considering all these, the Antarctic summer season is generally the period when expeditions are planned. Resupply operations and temporary surveys are usually done during this period as well. During these expeditions and operations, transportation is generally carried out by air and sea or a combination of these (Farreny et al, 2011).

After the Antarctic Treaty was signed in 1959, Antarctica became a continent entirely reserved for scientists. Scientific activities continue today with more than 100 facilities, including research stations and seasonal stations, that support the research of many countries operating in the region for almost half a century (COMNAP, 2017). The majority of the stations located here use mostly fossil fuels to generate their energy and release polluting gases into the atmosphere (Tin et al, 2009). In addition, research vessels navigating to the region increase carbon emissions with their activities in the Southern Ocean and maritime Antarctica.

1.1 Climate Change

Climate change is known as large-scale and long-term changes in weather events and average temperatures on our planet. The United Nations Framework Convention on Climate Change (1992) defined in its 1st article as “Climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.” Global warming simply refers to the rising surface temperature of the Earth. In other words, global warming is a symptom of a much larger problem such as human-induced climate change (NOAA, 2015).

In 4.5 billion years, the Earth has experienced many transitions between climates. In some periods, tropical hot climates occurred, as well as ice ages on the contrary. These natural changes depend on volcanic activities, solar activities, the Earth's distance from the sun and axial tilt. The Earth undergoes orbital changes in periods of 100,000 years, varying from ellipse to circle. In addition, the curvature, which is 23.5 degrees today, varies between 22 and 24.5 degrees in 41,000 years. Thus, in these periods, the amount and distribution of the energy that the Earth receives from the sun changes (NASA, 2020). To better understand climate change, it is essential to know the difference between climate and weather.

Three factors affect the energy flow in the Earth's climate system: solar energy, albedo, and the greenhouse effect. Albedo is defined as the amount of radiation from the Sun reflected from the surface. The regions with the highest albedo on the Earth's surface are the Arctic and Antarctica. While areas covered with snow or ice have the maximum albedo, the albedo of the oceans or the soil under this layer decreases as it melts (Acker et al, 2014). Changes in the rates of absorbed, emitted or reflected radiation affect the Earth's climate system, causing fluctuations in temperature, wind and precipitation. Therefore, albedo values have an important place in creating the local and global climate.

The greenhouse effect is expressed by the absorption of water vapor, carbon dioxide and other trace gases in the atmosphere. It absorbs terrestrial radiation emaneting from the Earth's surface and acts as a blanket on the Earth's surface, maintaining it hotter than it should be. Alterations in the atmospheric concentration of these gases can adjust the equilibrium of energy transfers between the atmosphere, space, land and oceans. (Muralikrishna et al, 2017). Although greenhouse gases are less in amount in the atmosphere compared to other gases, they have great effects on the warming of the world.

Apart from greenhouse gases, volcanic activities also play role in climate change. A volcano's impact on climate is not directly related to the explosiveness of the eruption, but directly to the sulphur content of the emissions reaching the stratosphere. These sulphur gases break down into small sulphate particles that stay in the stratosphere for several years and eradiate incoming sunlight, decreasing direct and total solar radiation reaching the soil (Robock, 1991).

1.1.1 Human impact on climate change

In the light of current data, the global warming observed in the last half-century cannot be explained by natural causes. Apparently, there is a climate change caused by human activities. Distinguishing human influence on climate requires examining the many natural changes that affect temperature, precipitation and other aspects of climate. As mentioned, volcanic eruptions also have climate-changing emissions. The gases released as a result of these activities cause an increase in small (aerosol) particles that partially reflect or absorb sunlight in the stratosphere. This results in a short-term surface cooling lasting approximately two to three years. Slow and repetitive changes in the Earth's orbital motion around the Sun have been changing the distribution of solar energy on Earth for much longer than hundreds of thousands of years. This is why the ice age cycles of the last 800,000 years have emerged (National Research Council, 2020). Interglacial cycles of the last 500,000 years are shown in Figure 1.1.

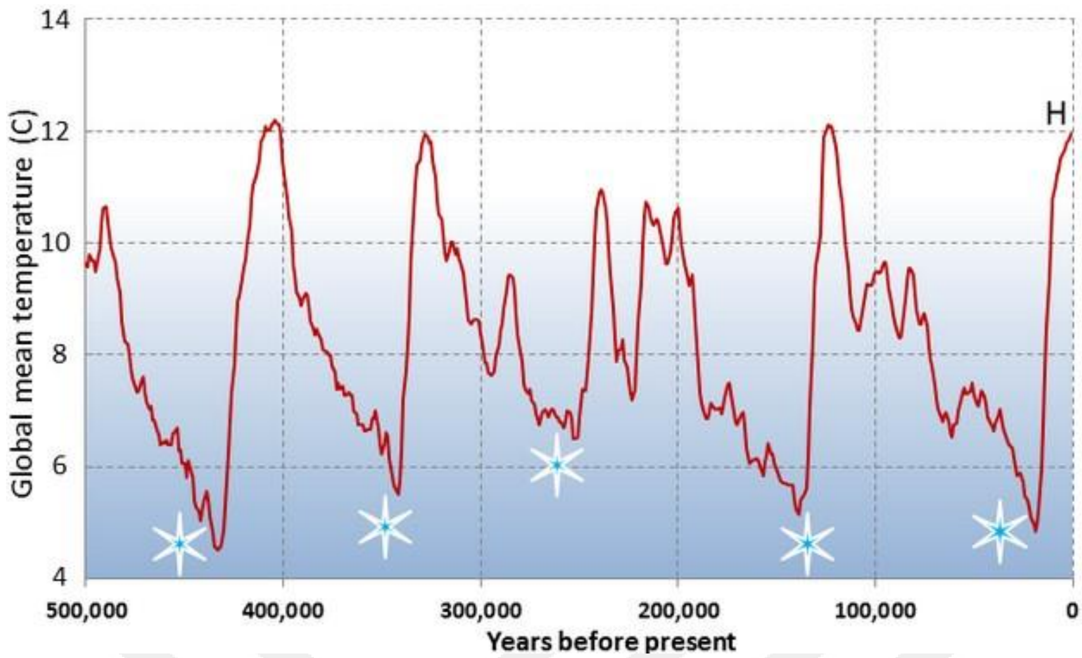

Figure 1.1 : Interglacial cycles of the last 500,000 years (Url-1).

The most obvious way to understand the human impact on climate change is to study the carbon footprint. In this context, one of the most important discoveries is the air bubbles examined in the ice core extracted at the Antarctic Vostok base. Scientists examining the ice core obtained the gas density information of the atmosphere thousands of years ago by examining the air bubbles in different layers of the ice accumulated over time (Souchez et al, 2003). In order to detect changes in the average temperature of the planet, it is necessary to look more closely at the geographical and temporal patterns of climate change (National Research Council, 2020).

In the IPCC 2021 report, human impact is shown as the most fundamental factor of climate change. The observed increases in greenhouse gas (GHG) concentrations since the mid-18th century are certainly due to human activities. Concentrations in the atmosphere have continued to increase since 2011. In 2019, it reached an annual average of 410 ppm for carbon dioxide (CO_2), 1866 ppb for methane (CH_4) and 332 ppb for nitrous oxide (N_2O). With regional variations, land and oceans have received an almost constant proportion (about 56% per year globally) of CO_2 emissions from human activities over the past six decades (IPCC, 2021).

1.2 The Role and Importance of Polar Regions in Climate Change

Polar regions act as the refrigerators of our planet. Glacial areas and sea ice regulate our climate by reflecting the heat from the sun with the albedo effect. Melting glaciers with climate change cause the world to warm up even more with greenhouse gases. Since it is not possible to interpret climate change with short-term data such as 100-200 years, it is necessary to reach data from very old dates. The most suitable area for this is Antarctica, which is isolated and remote from human activities.

Antarctica is a large continent covering an area of 14 million square kilometres. Cold weather affects a wide region extending beyond the equator in the form of water currents, migratory seabirds and marine mammals (Bharti and Gajananda, 2013). Antarctica is the highest and driest of all continents with an average altitude of 2300 meters. Almost all of the continent is covered by ice and its average thickness is over 2000 meters. This constitutes approximately 70% of the freshwater resources in the world (Bharti et al, 2015). As a result of the examination of ice cores extracted from various areas of the continent, information on climate cycles going back hundreds of thousands of years can be reached. A cross-section of subglacial Lake Vostok's drilling is shown in Figure 1.2. As an outcome of the examination of the Vostok ice core, it was determined that the temperature and atmospheric CO_2 and CH_4 concentrations in Antarctica were higher in previous periods. The study showed that the CO_2 and CH_4 concentrations are strongly correlated with the temperature values in Antarctica. While all the results show that greenhouse gases have a serious effect on the interglacial change, it has been determined that another factor is the decrease in the albedo effect of the glaciers due to melting (Petit et al, 1999).

Black carbon (BC) is released directly from incomplete combustion processes. BC is strongly capable to absorb light (Lack et al, 2014). Due to this characteristic, it is classified as a pollutant that changes temperature profiles, frequency of precipitation, surface albedo and snowfall rates and contributes to climate change (Pino-Cortés et al, 2021). The Antarctic region is isolated from major combustion sources related to human activities on the other continents. Therefore, there are no operations other than human activities at research stations, usage of snowmobiles for travel, operations of airplanes and research vessels in summer, and fishing that will cause BC emission in the Antarctic region (Hara et al, 2019). Although local contamination from these sources may result in temporarily high BC concentrations, BC emissions are negligible due to limited activity in Antarctica and fewer people compared to the other regions (Weller et al, 2013). Because of low BC concentrations, snow albedo reduction due to BC in Antarctica was found to be negligible (Marquetto et al, 2020). However, the potential for BC accumulation on snow and ice surfaces at low elevations has been observed throughout the McMurdo Dry Valleys (Khan et al, 2018).

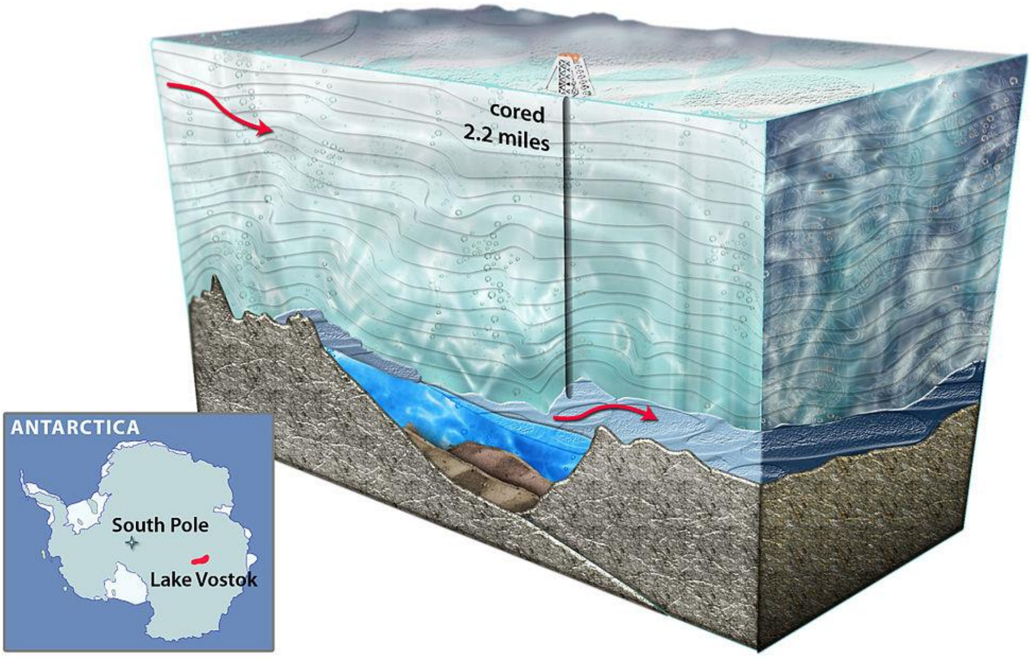

Figure 1.2 : Cross-section of Lake Vostok's drilling (Url-2).

In the winter periods, ocean water gets very cold and forms sea ice in the polar regions. Subsequently, the surrounding seawater becomes saltier because salt is left behind when sea ice forms. As seawater gets saltier, its density increases and it begins to sink. Surface water is pulled to replace sinking water, which eventually becomes so cold and salty, thus creating a current. This initiates deep ocean currents that set the global conveyor belt in motion. This deep water moves south, between the continents, crossing the equator to the ends of Africa and South America. The current travels around the coasts of Antarctica, where the water cools and sinks again, as well as in the North Atlantic. Hence, the conveyor belt is regenerated. As it moves around Antarctica, two sections separate from the conveyor and turn northward. One part moves to the Indian Ocean and the other to the Pacific Ocean. These currents are shown in Figure 1.3. The spherical conveyor belt is a powerful but easily broken process. Studies show that the conveyor belt can be affected by climate change. If global warming causes increased precipitation in the North Atlantic and melting of glaciers and sea ice, warm freshwater runoff to the sea surface may prevent sea ice from forming and cold, salty water from sinking (NOAA, 2007).

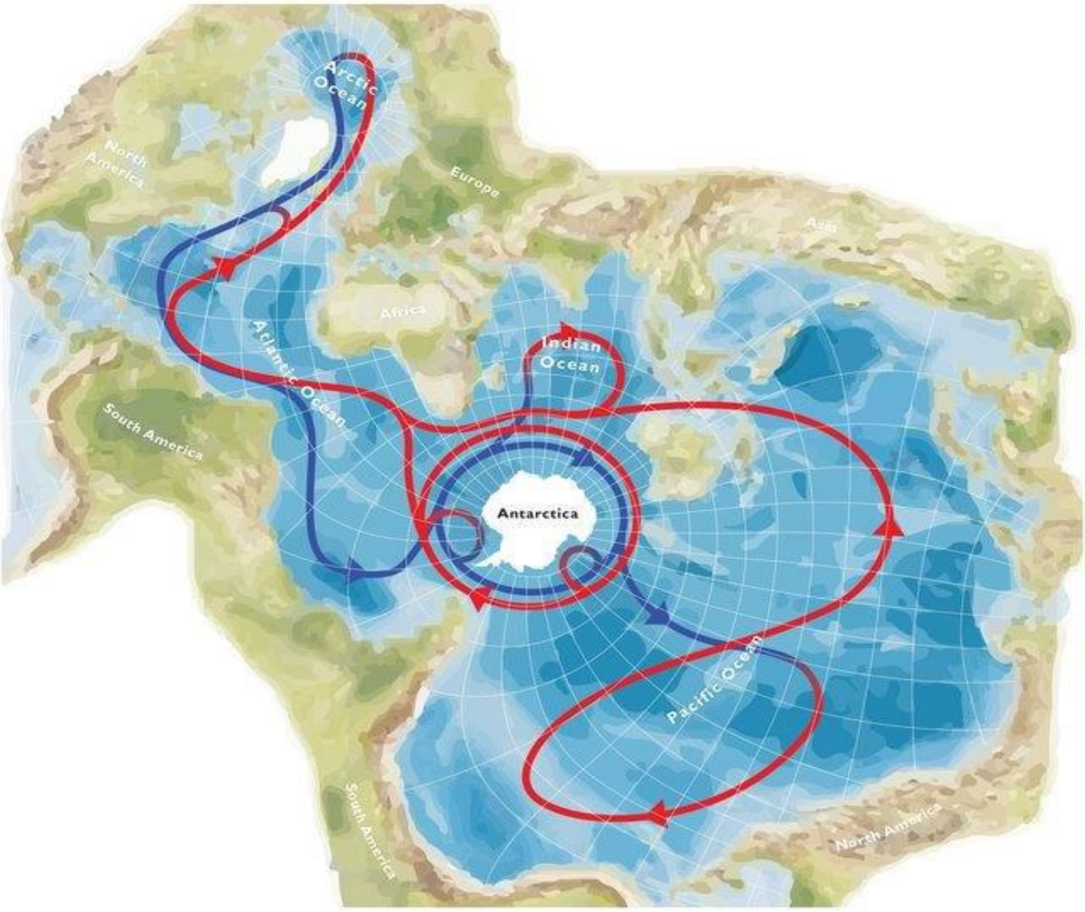

Figure 1.3 : The global conveyor belt is shown on a Spilhaus projection, with the surface current in red and deep current in blue (Meredith, 2019).

By the end of the 1970s, depletion of the ozone layer began to be observed. As a result of the observations made in Antarctica in the early 1980s, a depletion in the ozone layer was discovered (Farman et al, 1985). Ozone (O_3) is a gas that protects life on Earth by absorbing harmful UV radiation of less than 290 nm. UV radiation reaching the Earth's surface is largely proportional to the thickness of the upper ozone layer (WMO, 2019). Therefore, any reduction in the ozone layer has negative effects on life on Earth. Ozone is also an important and highly reactive gas for naturally occurring chemical transformations in the atmosphere. Ozone in both the stratosphere and the troposphere absorbs incoming solar radiation and outgoing infrared radiation, significantly warming the atmosphere. As a result, changes in stratospheric or tropospheric ozone lead to changes in climate (Salawitch et al, 2019).

1.2.1 Human activity in polar regions

Fishing activities, tourism and scientific research in the polar regions are the main human activities. Maritime activities in the Arctic region are much higher than in the south. Maritime activities in the southern ocean are mainly based on research, fishing and tourism. Polar research expeditions are currently being carried out in both polar regions. While research vessels are mostly used in the Arctic, scientific studies are usually conducted at seasonal or year-round research stations in Antarctica. A total of 30 countries have 112 scientific bases including research stations by 2017. 71 of them are seasonal stations that are not visited in Antarctic winter and the other 41 stations are open year-round. Every year about 4400 scientists work in these stations in summer and approximately 1100 of them continue research in winter (COMNAP, 2017). For this reason, Antarctica is the first place that comes to mind when polar research is considered within the scope of scientific studies.

In addition to scientific research activities in the Antarctic continent, the number of visitors in tourism has exponentially increased in the last 20 years. Although the Covid-19 pandemic has impacted touristic activities in the short term (Hughes and Convey, 2020), approximately 74,000 tourists visited Antarctica in the 2019/20 season (IAATO, 2019). The majority of tourists land in a small number of sites located on the Antarctic Peninsula and offshore islands, mostly between November and March (IAATO, 2017). The duration of the summer tourism season is slowly expanding over time, increasing the pressure on the visited locations (Bender et al, 2016). In very little ice-free terrain, infrastructure, including runways, research stations, and piers continue to be developed or expanded to support scientific and tourism activities (Hughes et al, 2011; Pertierra et al, 2017).

Scientific research stations are spread to almost all regions of the Antarctic continent. However, the studies are usually concentrated in the West Antarctic Peninsula, which is close to the coasts of Chile and Argentina, compared to the interior regions and East Antarctic coasts. Subsequently, more stations and, as an inevitable consequence of this, more intense anthropogenic pollution are observed in the regions where the scientific research is dense. As a consequence, ASPA (Antarctic Specially Protected Areas) were designated in Annex V of the Madrid Protocol (Hughes et al, 2021). As a result of the observations and research made for special protection areas, although experts reported improvement compared to the past within the framework of waste management, especially the remains of old-style stations, garbage dumps and fuel stations cause pollution. While the exposed ashes and waste dump residues containing dangerous substances are noted in the records, the harsh and windy air of Antarctica also causes the spread of this pollution. Unfortunately, it has been observed a wide variety of waste materials (construction waste, insulation material, cardboard, paint buckets, batteries, fire extinguishers) were improperly stored outside and no measures were taken to prevent dispersal in some cases (Braun et al, 2012). Hydrocarbon contamination with visible oil/fuel contamination in water bodies and soil is conspicuous throughout the existing road network and within the boundaries of almost all stations. Oil pollution is mainly caused by spills during fuel transfer or by damaged vehicles. Leakage of station pipelines and tanks leads to contaminated soil because of spreading by heavy rainfall (Peter et al, 2008).

1.2.2 Logistics in polar studies

The most basic and common method of transportation to the Antarctic continent is by sea (Farreny et al, 2011). Apart from this, the combined use of air and sea routes is also widely used, especially in travels to the Antarctic Peninsula. Countries such as Australia, Chile and Argentina, which are geographically close to the continent, have preferred locations that are close to them to establish research stations. The distance from the European continent to the closest parts of Antarctica is about 8 to 10 thousand nautical miles. This corresponds to approximately 30-35 days of the expedition. In addition to this voyage, many countries prefer the ports of Ushuaia, Argentina, or Punta Arenas, Chile to carry out the supplies to be made during the research (Farreny et al, 2011). Some countries send personnel and cargo over Argentina or Chile by plane instead of ocean-going expeditions on a research vessel. In the next stage, the researchers are transported to the stations by sea via Chile or Argentina. Some of the major countries with well-established research stations on the continent can also make direct flights to the airstrips on the continent.

Ships are the means of transportation that cause the most pollution due to unit fuel use in the world (Corbett & Fischbeck, 1997). Since most of the expeditions to Antarctica are carried out by sea, the impact of logistics on the environment is quite high. Greenhouse gas and carbon emission calculations are made for all stages of the expedition to the continent. When each pollutant factor such as air-sea transportation, use of snowmobiles around the station, energy production at the station, and heating is calculated one by one, it is seen that the largest share is transportation. According to the South Pole Greenhouse Gas Calculation 2017 report, logistics activities cause the most carbon and greenhouse gas emissions on the continent. The biggest polluting action after the expedition to the continent was the transportation of personnel before the expedition (South Pole, 2018). This is ultimately linked to polar logistics.

1.3 Literature Review

There are numerous sources in the literature on the activities of merchant ships. Greenhouse gas emissions of containers, bulk carriers, and tankers have been assessed in those studies. In addition, studies have been conducted on the fishing vessels impact on the environment. With the increase in the size of the ships, gas emissions have also increased significantly. Ships emit carbon dioxide (CO_2), nitrous oxide (NOx), sulphur oxide (SOx), carbon monoxide (CO), unburned hydrocarbon (HC), and particulate matter (PM_{10} – $PM_{2.5}$) into the air. These gases trigger climate change and cause serious air pollution (Richter et al, 2004; Traut et al, 2018). Bulk carriers, container ships and tankers account for 80% of emissions from maritime transport (Yau et al, 2012).

Chang and Wang (2012) assessed the efficient strategies to reduce emissions in port areas. According to their study, reducing the ship speed to 12 knots was shown as the most effective method in reducing fuel consumption and emissions. It was determined that using shore energy in ports reduced CO_2 and PM emissions. Chang and Wang (2013) investigated the fuel consumption and associated CO_2 emissions of Capesize, Panamax, Supramax and Handysize dry bulk carriers using the activity-based method. The reductions in the amount of emission and energy were estimated according to 3 step reduction rates of the ship speed. It was determined that gradually reducing the speed reduced the fuel consumption by proportion to the reduction level, and as a result, CO_2 emissions decreased in comparison to the higher speed.

Linstad et al. (2013) conducted energy efficiency research by comparing the fixed costs of bulk carriers with fuel costs. At this point, it was considered that setting stricter rules for newly built ships would increase energy efficiency as a method. It was determined that the fuel consumption of slenderer ships decreased, and thus emissions and expenses decreased.

Sun et al. (2013) compared the performance of transoceanic vessels by focusing on the energy consumption and greenhouse gas emissions of inland river transport. Container transportation data in the Yangtze River, China were collected and analyzed in both calm weather and real navigation conditions. As a result of the research, it was determined that the environment and inland water river vessels affected the operational energy efficiency significantly.

Acomi and Acomi (2014) discussed the concept of the Energy Efficiency Operational Index (EEOI), which was developed to assist shipowners and ship operators in the process of establishing a mechanism to limit or reduce emissions from ships in operation. It presented a tracking tool that shows the mass of CO_2 released for each transport job. In this study, it was shown how a commercial software could predict the EEOI data before the voyage by comparing it with the actual values calculated on the ship.

Zis et al. (2014) considered that differences in port operating policies have the potential to reduce emissions from shipping. However, it was also stated that their effectiveness would vary. In this study, it was presented a consistent methodology for emission reduction based on ship port call data. CO_2, SO_2, NOx, and BC emissions from container ship activities close to the port were estimated in the article. Two emission reduction policies were considered for typical container terminals. As a result of the study, it provided serious reductions in CO_2, SO_2 and NOx emissions thanks to the speed reduction policy. However, it was reported that speed reduction policies can increase BC emissions.

Chang and Jhang (2016) implemented the Green Flag Program in their research to assess the benefits of reducing speed and fuel transfer for large commercial vessels (bulk and container) entering Kaohsiung Port. This study adopted an activity-based model to calculate fuel consumption and emissions, as well as set up two scenarios. Container and bulk carriers had a reduction in SO_2 and CO_2 emissions. It was determined that large ships were more environmentally friendly than small ships. It was found that container ships benefited from both speed reduction and fuel transfer, while bulk carriers benefited only from the first.

Li et al. (2019) carried out speed optimization of a 4250 TEU container ship, considering the effects of sea weather and voluntary speed loss on ship navigation. A speed optimization model was established for a single voyage where the objectives were to minimize fuel consumption and ship operating costs. Ship speed optimizations with and without voluntary reduction of speed were performed. The research resulted that the optimization of the model with voluntary deceleration was significantly different from those without voluntary deceleration. In order to make the optimization results more accurate and more suitable for real voyage conditions, it was determined that the voluntary speed loss should be taken into account in the optimization model.

Wan et al. (2020) found that pollutant emissions from ships could increase with expanding international trade and shipping fleet size, posing a serious but often overlooked threat to public health. China's three major port areas were selected for the research. This study examined emissions of key pollutants such as NOx, PM_{10}, $PM_{2.5}$, HC, CO, SOx, CO_2, CH_4 and non-methane volatile organic compounds (NMVOC) using an automatic identification system (AIS) data. All in all, it showed that ships in the Yangtze River Delta generated the most emissions among the three regions studied.

Tzannatos (2010) applied a methodology based on in-port ship activity in manoeuvring and berthing of coastal ferries and large cruise ships calling at Piraeus cruise port to estimate the emission of mother ship exhaust pollutants over twelve months in 2008-2009. Estimated emissions were analyzed in terms of gas types, seasonality, activity and logistics sector. The results found that ship emissions at the Piraeus cruise port reached 2600 tons per year. It was observed that summer emissions and related effects were greater.

Molders et al. (2013) developed an activity-based emissions model to determine cruise ship emissions. The calculated emissions depended on the cruise data and the characteristics of the ships. Two recommended management actions were identified for the 2008 voyage season of cruise ships due to PM and other gases: a predefined speed in Glacier Bay and the implementation of an Emissions Control Area (ECA) in Alaska in general. As a result of the study, it was determined that the ships emitted PM in Glacier Bay more before ECA was established in the region. Additionally, the speed reduction policy reduced PM emissions dramatically and average visibility marginally increased.

Tichavska and Tovar (2015) stated that the exhausts generated as a result of the combustion of ship fuels were equally harmful in ports due to their urbanized character, as well as very close to the environmentally sensitive mainland and island coasts. For the first time, the exhaust pollutants associated with ship and ferry operations in the Port of Las Palmas was estimated. The emissions assessment was based on a full bottom-up model and messages transmitted by the Automatic Identification System (AIS) in 2011. Emission maps verified the location of hotspots at berths dedicated to cruise and ferry operations. Feasibility studies were recommended for automated mooring, LNG refuelling facilities, as well as coastal energy services, which prioritized the berthing of the maritime sectors.

Tzannatos et al. (2015) referred to the high coastal shipping activities in the Greek seas and the environmental vulnerability of the Greek coasts. In this context, the use of liquefied natural gas (LNG) to power island ferries represents a promising alternative to petroleum fuel to achieve a significant reduction in SOx, NOx and PM exhaust pollution. The connection between the Greek Dodecanese Islands and the main port of Piraeus was analysed with an oil versus LNG fueled ferry line. The results showed that, compared to conventional fuel oil, natural gas currently offers a favourable alternative in terms of private costs as well as unforeseen costs from ship exhaust pollution. It was suggested to encourage new fuels for merchant ships as well as ferries. The aim of the article was to support green energy in maritime transportation in terms of EU environmental programs.

Papaefthimiou et al. (2016) applied a bottom-up methodology based on in-port ship activities to calculate exhaust pollutant values (NOx, SO_2 and $PM_{2.5}$) during departure/manoeuvre and hotelling for international cruise voyages. Estimated emissions were analyzed in terms of gas types, seasonality and activity. In terms of total in-port inventory for cruise ships, NOx dominates, followed by SO_2 and $PM_{2.5.}$ The emission generated at hotelling corresponded to almost whole total emissions and was found to be significantly higher than those produced during the manoeuvring activities of the ships. Seasonality was found to play an important role, as summer emissions and associated impacts are more profound.

Chou et al. (2021) assessed the estimation of CO_2 emissions and analyzed energy efficiencies using the Energy Efficiency Operational Index (EEOI) for ferries and cruise ships navigating among islands around Taiwan. A comparative analysis of energy efficiency parameters showed that hybrid diesel-electric ferries had better efficiency than conventional full diesel ferries, while high-speed cruise ships had greatly lower efficiency than medium speed cruise ships. Based on these results, some potential policies were suggested to reduce CO_2 emissions from in-port ferries and island cruise ships.

Farreny et al. (2011) emphasized that the increase in tourism to the Antarctic continent could bring with it not only local but also global environmental effects. These latter effects, mainly from transportation, had often been overlooked. As a result, there was a lack of data on the global impacts of Antarctic tourism in terms of energy consumption and carbon dioxide emissions. In the study, it was presented and applied a methodology to measure CO_2 emissions both for the Antarctic ship fleet as a whole and per passenger. The results showed that the average tourist trip to Antarctica resulted in 5.44 tons of CO_2 emissions per passenger, or 0.49 tons of CO_2 emissions per passenger and day. About 70% of these emissions were from cruising and 30% from the flight, highlighting the global environmental importance of local transport for this type of tourism.

Contemporary research on reducing greenhouse gas emissions from ships and the impact of this on the environment are reviewed above. These studies are classified as speed and route optimization, alternative fuel usage, determination of emission control areas, changing ships' engine types and the effects of Antarctic tourism on the environment. In the literature, no specific study could be found on the emissions of ships engaged in scientific research voyages. It was observed that studies on the environmental impact of research ships making scientific voyages to Antarctica on the Antarctic region and the southern ocean are limited. Therefore, this study is important as it will fill the knowledge gaps on carbon emissions of the scientific expedition to Antarctica.

1.4 Purpose of Thesis

The aim of this study is to analyze and estimate the carbon emissions of Antarctic scientific expeditions, to compare the emissions of different scenarios, and to recommend measures to reduce these emissions.

2. METHODOLOGY

There are many methods for calculating the carbon emissions of ships. These are divided into analytical methods and statistical methods. The analytical methods used in the calculation of ship emissions are also divided into two parts: the stoichiometric method and the carbon balance method. The stoichiometric method can be applied if the carbon content of the fuel and fuel consumption per hour are known to find out the mass of CO_2 emissions from exhaust gases of the ship engines. To determine the mass of CO_2, the stoichiometric oxidation of carbon in the burnt fuel composition will be used. The CO_2 emission reaction from burning a kilogram of fuel is given in equation 2.1 (Cosofret et al, 2016).

$$C + O_2 \rightarrow CO_2 + Q_c \tag{2.1}$$

In this reaction, oxygen and carbon dioxide are calculated on the basis of one kilomole, then 12 kilograms of carbon is burned with 32 kilograms of oxygen, and it results in 44 kilograms of carbon dioxide. Q_c in the equations means the heat released as a result of combustion. In equation 2.2, it is given the reaction when the fuel with a known carbon content by mass is burned.

$$aC + \frac{32a}{12} O_2 \rightarrow \frac{44a}{12} CO_2 + Q_c \tag{2.2}$$

For an amount of carbon burned “a” kg C / kmole from fuel, the carbon emission of an engine can be obtained by multiplying the mass of 3,667a kg carbon dioxide by the hourly fuel consumption value.

The carbon balance method can be used to the extent that the CO_2 concentration in the exhaust gases of the machines can be determined. To use this method, CO_2 emissions must be measured using a gas analyzer. It is also necessary to measure hourly fuel consumption and feeding air parameters (pressure and temperature) and find the percentage of chemical components of the fuel. To estimate the mass of certain CO_2 emissions, the calculation algorithm of the Technical Code for the control of nitrogen oxide (NOx) emissions in diesel generators should be used (IMO, 2008).

In statistical methods, the calculation of CO_2 emissions from ships is roughly estimated. It is based on emission factors for different fuels of ships and various operating modes. Also, different types of ships affect emission calculation, as well as fuel type. The formula for the mass of CO_2 emissions is given in equation 2.3 (Cosofret et al, 2016).

$$m_{CO2} = \frac{C_h \, x \, EF_{CO2}}{1000} \; tonne \; CO_2/h \tag{2.3}$$

In this equation; m_{CO2} is the mass of CO_2, where C_h is fuel consumption per hour and EF_{CO2} is the carbon dioxide emission factor (Cefic-ECTA, 2011).

In this method, there are two options for calculating carbon dioxide emissions. The first is the determination of the correct emission factor according to the fuel. The second is the calculation based on fuel consumption according to the type of ship and its engine. It is necessary to know how much fuel to be burned for 1 kWh of energy. These fuel values are also specified by engine manufacturers in the technical documents. In the next steps, carbon emissions are estimated with formulas used in the light of statistical data obtained by ship types (Cosofret et al, 2016). The carbon content of each fuel type is constant and is not affected by engine type or other parameters when the mass of CO_2 emissions is determined in kg per tonne of the fuel consumed. CO_2 emission factors for the main and auxiliary engines on board, calculated based on emission inventories, are as follows (IMO, 2012).

- for the Heavy Fuel Oil (HFO) type of marine fuel: EF_{CO2} = 3114 kg CO_2/tonne of fuel;
- for the Marine Diesel Oil (MDO) type of marine fuel: EF_{CO2}= 3206 kg CO_2/tonne of fuel;
- for the Liquid Natural Gas (LNG) type of marine fuel: EF_{CO2}= 2750 kg CO_2/tonne of fuel.

2.1 Diagrams of Scenarios and Stages

Two scenarios are prepared to estimate emissions from Antarctic expeditions. In the first scenario, the Antarctic expedition is carried out using only a research vessel from Europe to Antarctica. In the second scenario, the Antarctic expedition is carried out by arriving in Chile from Europe by air, and then getting on the research ship. In both scenarios, the same ships are used and research is conducted in the same area in equal time.

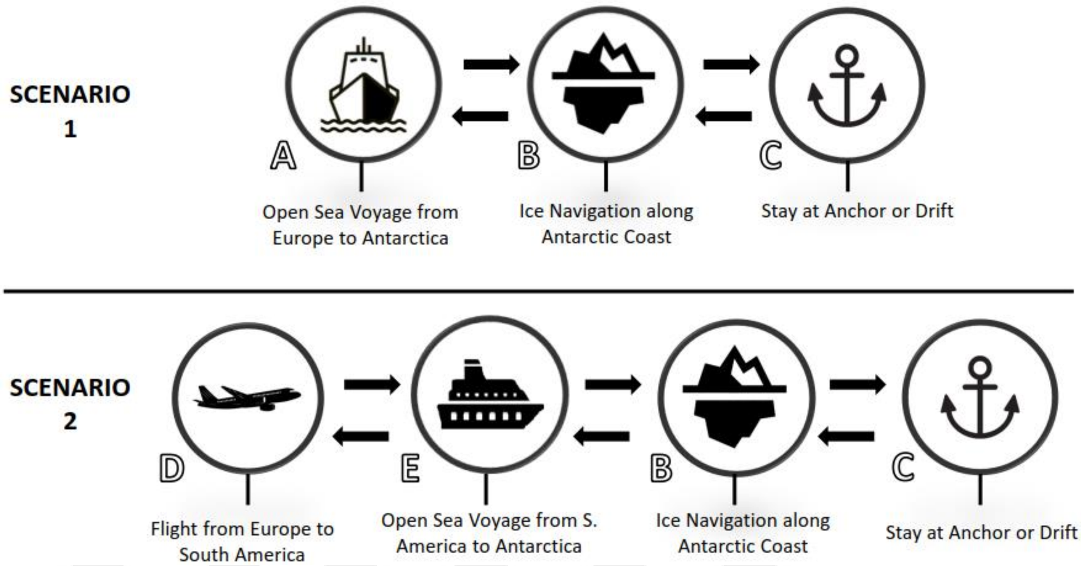

Figure 2.1 : Diagram of scenarios.

A Diagram of scenarios is shown with its stages in Figure 2.1. The sum of the emissions released in the phases coded with letters will give the total emissions released in the scenario. The code with the letter A means open sea voyage from Europe to Antarctica, the code with the letter B means ice navigation along the Antarctic coast and the code with the letter C means stay at anchor or drift for 30 days. In the second scenario, the sum of the emissions released in the phases coded with letters will give the total emission released in the scenario as well as in the first scenario. The code with the letter D means flight from Europe to Chile and the code with the letter E means open sea voyage from Chile to Antarctica. B and C codes mean the same as the first scenario.

So, the total emission for the first scenario is the sum of codes A, B, and C. Along the same line, the total emission for the second scenario is the sum of codes D, E, B, and C.

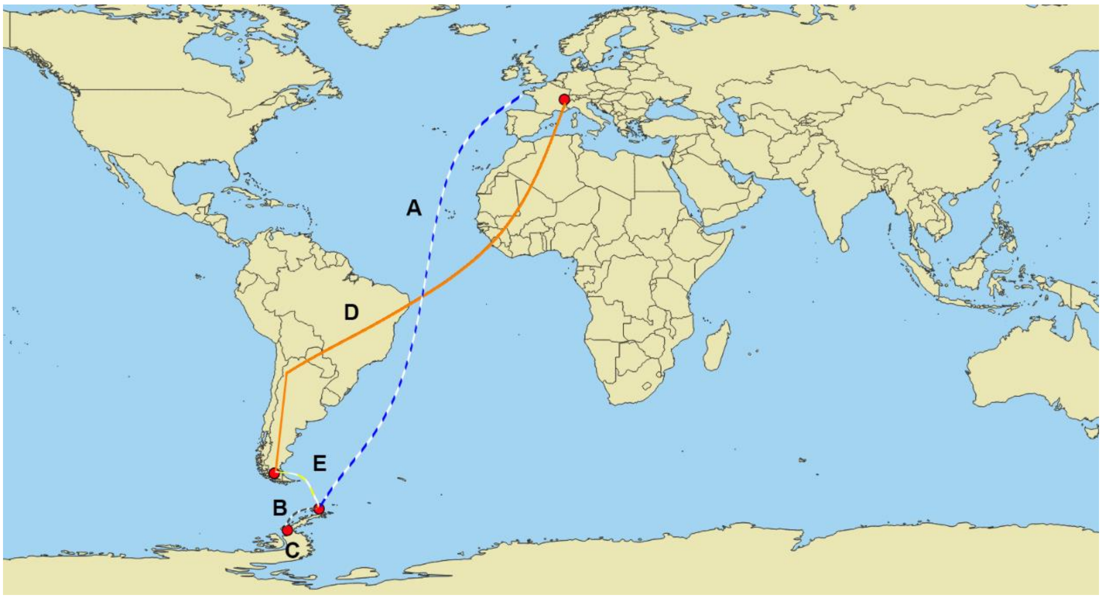

Figure 2.2 : The routes of scenarios.

The routes of the scenarios indicated by the codes are given on the map in Figure 2.2. Code A, dashed blue route, shows the open sea voyage from Europe to Antarctica, Code B dashed grey route shows ice navigation along the Antarctic coast, Code C indicates the expected point for the research phase, Code D orange firm line indicates aircraft route, and Code E dashed yellow route represents the open sea voyage from Chile to Antarctica.

2.1.1 Research vessel carbon emission scenario for Antarctic expedition

In this study, a diesel ship was selected as the research vessel. As per the scenario, it was calculated that the research vessel would sail from Europe to the West Antarctic region. The statistical method is preferred in this study and carbon emission factors were used for calculations. CO, NOx, SOx, NMVOC and PM_{10} emissions are determined according to the factors contained in the European Monitoring and Evaluation Programme / European Environment Agency (EMEP/EEA) 2019 guidebook (EMEP/EEA, 2019). Because the EMEP/EEA 2019 guidebook does not include CO_2 emission factors, these factors were taken from International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC) 202(63) resolution for marine diesel. CO_2 emissions were estimated using this data (IMO, 2012).

Table 2.1 provides emission factors of pollutant gases other than CO_2 for MDO type fuel. The mass of emitted pollutants is detected by using these factors at a time when fuel consumption is known.

Table 2.1 : Emission factors except CO_2 (EMEP/EEA, 2019).

Pollutant	EF (kg/ton) Anchor/Drift	EF (kg/ton) Navigation
NOx	59.7	60.6
SOx	10	10
CO	7.4	7.4
NMVOC	1.8	2.4
PM_{10}	1.4	1.5

The calculation formula of the mass of pollutant gas emissions is shown in equation 2.4.

$$m_{pg}=\frac{(C_f \text{ x } EF_{pg})}{1000}\ tonne \tag{2.4}$$

In this equation; C_f represents fuel consumption, m_{pg} is the mass of emitted pollutant gas, and EF_{pg} is the emission factor of pollutant gas are defined.

Considering the ships used as research vessels in the Antarctic region, it was determined that 3600 kW of power would be sufficient for 24 people (de Waal et al, 2018). Wärtsila 6L20 model 1200 kW marine diesel engine was preferred because it provides the most data in emission calculations in terms of fuel consumption (Wärtsila, 2020). Although it is predicted that 3600 kW of marine diesel engine shall be enough, calculations were made on 4 pieces of Wärtsila 6L20 model 1200 kW marine diesel engine with a total of 4800 kW and one of them is considered as spare.

Table 2.2 : Specific fuel consumption (SFOC) (Wärtsila, 2020).

Load	g/kWh
100%	196
85%	190
75%	190
50%	194

In Table 2.2, the specific fuel consumption values of the diesel engine are given according to the percentage of the load. When calculating fuel consumption, the engine load at the navigation state was calculated as 85%, at the ice navigation state was 75% and at the anchor or drifting state as 50%. The consumption calculation formula is given in equation 2.5.

$$C_f = \frac{(P \times L \times SFOC \times 24 \times t)}{1000000}\ tonne \tag{2.5}$$

In the equation; C_f represents fuel consumption, P is engine power, L is engine load, SFOC is specific fuel oil consumption, and t is days on the voyage are determined.

The distance from Europe to the region was determined as 8500 nautical miles and a total of 17000 nautical miles were thought to be made. Since the average economic speed of the research vessels was 10 – 12 knots, the average speed of 12 knots was used in the calculations (Url-3). Although the expedition is conducted during the summer season, it is thought that there are glaciers and sea ice in the areas approaching the coast (AARI, 2021). The ice navigation speed was also determined as 3 knots based on the ships operating in the region. Expedition plans are made based on the conditions of the Antarctic summer season which is between December and March.

Although sea ice is less than in winter during the Antarctic summer season, it is present on the coasts. When the Antarctic sea ice maps published by the Arctic and Antarctic Research Institute (AARI) are examined for March 2021, it is seen that the sea ice rate in the Weddell Sea, Amundsen Sea and the Ross Sea regions of West Antarctica is higher than in East Antarctica (AARI, 2021). Using the Antarctic Digital Database Map Viewer page prepared by the Scientific Committee on Antarctic Research (SCAR), the distance of sea ice extent from the Antarctic coast was measured (Url-4). As a result of the measurement, 50 to 100 nautical miles of sea ice formation was detected in West Antarctica. In the calculations, the average ice navigation distance was taken as 75 nautical miles.

Calculations were made according to three different states of the research vessel. These conditions are indicated as the open sea voyage, ice navigation and waiting at anchor or drifting. Since the total cruising distance is 8500 nautical miles and the average ice navigation distance is 75 nautical miles, the open sea voyage distance makes 8425 nautical miles. At an average speed of 12 knots per hour, our open sea cruise lasts about 29 days. The ice navigation lasts 1 day as it can be carried out at a speed of about 3 knots per hour. In light of this information, the cruising phase of the expedition is 30 days. Researches and laboratory studies to be carried out on the ship at sea whilst waiting at anchor as far as possible and subject to seabed suitability or drifting in the region. By launching boats over the ship, research studies are carried out in the vicinity of the ship and the nearby bays. Additionally, scientific studies are carried out in different disciplines by boat thanks to landing onshore. Within the scope of the research, the time at anchor or drift was determined as 30 days when it is taken into account the research carried out by many other countries in the region. In addition to determining the energy-derived emissions obtained by the ship's engine, the environmental impact of boat operations is taken into account. Arrival from Europe, research phase and departure from Antarctica are planned as a total of 90 days and emissions are determined accordingly.

2.1.2 Airline integrated carbon emission scenario for Antarctic expedition

In the first scenario, the voyage from Europe to Antarctica is carried out by a diesel research vessel. In the second scenario, scientists and research vessel crew arrive by air in Punta Arenas, Chile. The expedition is made to the West Antarctic region from Chile on a research vessel.

The fuel consumption of flights from Europe to Punta Arenas is calculated using the aircraft fuel consumption tables. Boeing 787-8 is selected for intercontinental flight and Airbus A320 is used for domestic flights in Chile (ICAO, 2018). London Heathrow Airport in England is preferred for departure from Europe and a flight to Punta Arenas is designated with a stop in Santiago. The flight route and total consumptions are given in Table 2.3. The flight distance is 13826 kilometres for one direction and the total fuel consumption in one way is calculated as 77.13 tons.

Table 2.3 : Flight distance and fuel consumption of aircrafts

Leg	Distance (km)	Fuel (ton)
London - Santiago	11647	68.297
Santiago - P. Arenas	2179	8.833

Table 2.4 : Fuel consumption of aircrafts per distance (ICAO, 2018).

Distance (km)	Fuel Cons. (ton) Airbus A320	Fuel Cons. (ton) Boeing 787-8
231.5	1.672	2.638
463	3.430	5.517
926	4.585	7.708
1389	6.212	10.600
1852	7.772	13.421
2778	10.770	18.910
3704	13.650	24.280
4630	16.452	29.557
5556	N/A	34.780
6482	N/A	39.954

Table 2.4 (continued) : Fuel consumption of aircrafts per distance (ICAO, 2018).

Distance (km)	Fuel Cons. (ton) Airbus A320	Fuel Cons. (ton) Boeing 787-8
7408	N/A	45.090
8334	N/A	50.200
9260	N/A	55.290
10186	N/A	60.350
11112	N/A	65.390
12038	N/A	70.420
12964	N/A	75.430
13890	N/A	81.220
14816	N/A	84.440

Fuel consumptions of aircrafts per distance are given in Table 2.4. Fuel consumptions are interpolated using the values given in Table 2.4.

Emissions from these fuel consumptions were calculated using the emission factors in the IPCC guidebook which are given in Table 2.5 (IPCC, 1996). Emission calculations from the engines of aircraft are generally prepared for landing and take-off operations (LTO). It is stated that the fuel consumption of the LTO phase is 10% of total fuel consumption. Emission factors of the average fleet are determined for calculating the fuel consumption of the LTO phase.

Table 2.5 : Default emission factors and fuel consumption for aircraft (IPCC, 1996).

International	LTO (kg/LTO) – Average Fleet	LTO (kg/LTO) – Old Fleet	Cruise (kg/ton)
Fuel	2500	2400	-
SO_2	2.5	2.4	1.0
CO	50	101	5
CO_2	7900	7560	3150
NOx	41	23.6	17
NMVOCs	15	66	2.7
CH_4	1.5	7	0
N_2O	0.2	0.2	0.1

The distance from Punta Arenas port to the region was measured as 875 nautical miles. Since the ice navigation distance is 75 nautical miles, as in the first scenario, the open sea voyage is 800 nautical miles. The open sea voyage takes 2.7 days with an average speed of 12 knots. Ice navigation lasts 1 day as in the first scenario. For the two scenarios to be analyzed comparatively, the work in the drifting phase is the same as in the first scenario. The time spent at anchor or drift is determined as 30 days. The formula given in equation 2.5 will be used to calculate the emissions occurring in cases of the open sea voyage, ice navigation and waiting at anchorage/drift of the research vessel. Since the research vessel is the same as the ship in the first scenario, the engine load and fuel consumption values per kWh in Table 2.2 will be used.

2.1.3 Carbon emission of boat and helicopter operations during research

In both scenarios, a 30-day research period starts when the research vessel arrives at the study area and starts to wait at anchor or drift. Scientists works both in the laboratories on the ship and the coast of Antarctica. For this reason, they have to go ashore every day and then return to the ship. These operations are carried out by boat and helicopter operations.

For Zodiac boats to operate, gasoline is required and as an outgrowth, greenhouse gases are released. It is foreseen to use boats for 1 hour per day during the research process. This corresponds to a total of 30 hours of boat usage while drifting or waiting at anchor. Zodiac Milpro Heavy Duty boats are used in the majority of research vessels in Antarctica. These boats have 115 hp Yamaha outboard motors.

Table 2.6 : Fuel consumption of zodiac boat (Url-5).

RPM	Fuel (liter/h)
Idle	1.5
1000	1.9
1500	2.3
2000	3.8
2500	7.2
3000	9.8
3500	13.2
4000	17.4
4500	22.0
5000	24.2
5500	28.8
6000	36.7

The consumption of the outboard boat engine by RPM is given in Table 2.6. The recommended speed of the manufacturer is between 3000-4000 RPM (Yamaha, 2014). No special case is specified for usage in a cold environment in the user's manual; therefore, calculations are made over 3500 RPM. Fuel consumption calculation is given in equation 2.6. Since the fuel consumption is given in litres by RPM, the mass of the burned fuel is found by multiplying the density of gasoline, which is 0.737 tons per m^3.

$$C_f = \frac{C_h \text{ x h x } 0.737}{1000} \text{ tonne} \quad (2.6)$$

In this equation; C_f represents fuel consumption, where C_h is fuel consumption litre per hour and, h is working hour.

Table 2.7 : Emission factors for 4 stroke gasoline motor (EMEP/EEA, 2019).

Pollutant	EF (kg/ton fuel)
CO_2	3256
CO	348
NMVOCs	29.2
NOx	25.8
TSP	0.188
PM_{10}	0.188
$PM_{2.5}$	0.188
NH_3	0.005

Emission factors for a 4-stroke gasoline engine are given in Table 2.7. Emission values are calculated by multiplying the total fuel consumption in boat operations with the emission factors.

Researchers sometimes need helicopters as a transportation vehicle in Antarctica but not very often. MBB Bo 105 model helicopters are preferred for helicopter operations in most of the regions where research is carried out in Antarctica. Helicopter operation during the research phase is planned as 8 flights of half an hour duration. A total of 4 hours of helicopter usage is figured out during the research process in both scenarios. MBB Bo 105 type helicopters have twin engines with 420 SHP (shaft horse power).

Table 2.8 : Fuel consumption & emissions of the helicopter (Rindlisbacher et al, 2015).

Emission (kg)	LTO	One Hour Ops.
Fuel cons.	32.8	203.5
CO_2	103.3	641
NOx	0.13	1.04
HC	0.96	1.82
CO	1.27	2.28
PM non-volatile	0.005	0.035

Fuel consumption and emission values for LTO and one hour of operation are given in Table 2.8. Since there are as many landings and take-offs as the number of flights, the LTO values in Table 2.8 are multiplied by the number of flights, and the emission amount is calculated for the LTO phase.

3. RESULTS AND DISCUSSION

3.1 Emission Calculations for First Scenario

3.1.1 Emission during open sea voyage (A)

The research vessel navigates from Europe to Antarctica in this scenario. It completes its open sea voyage distance of 8425 nautical miles at an average speed of 12 knots in 29 days. In order to make an emission estimation, first of all, the fuel consumption must be calculated during this expedition.

Table 3.1 : Fuel consumption of the vessel during the open sea voyage.

Parameters	Value
Engine Power (kW)	3600
Engine Load (%)	85
SFOC (g/kWh)	190
Duration (day)	29
C_h (kg)	581.4
C_f (ton)	404.7

Table 3.2 : Estimated emissions of open sea voyage.

Pollutant	EF (kg/ton fuel)	Emission (ton)
CO_2	3206	1297
NOx	60.6	24.5
SOx	10	4
CO	7.4	3
NMVOC	2.4	1
PM_{10}	1.5	0.6

The open sea voyage fuel consumption of the research vessel is calculated as stated in equation 2.5 and shown in Table 3.1. The emission estimates as a result of the fuel burnt in the open sea are given in Table 3.2. It is determined that 98% of all emissions are CO_2 emissions. NOx gas has the highest emission after carbon dioxide. Figure 3.1 shows the comparative graph of gases other than CO_2.

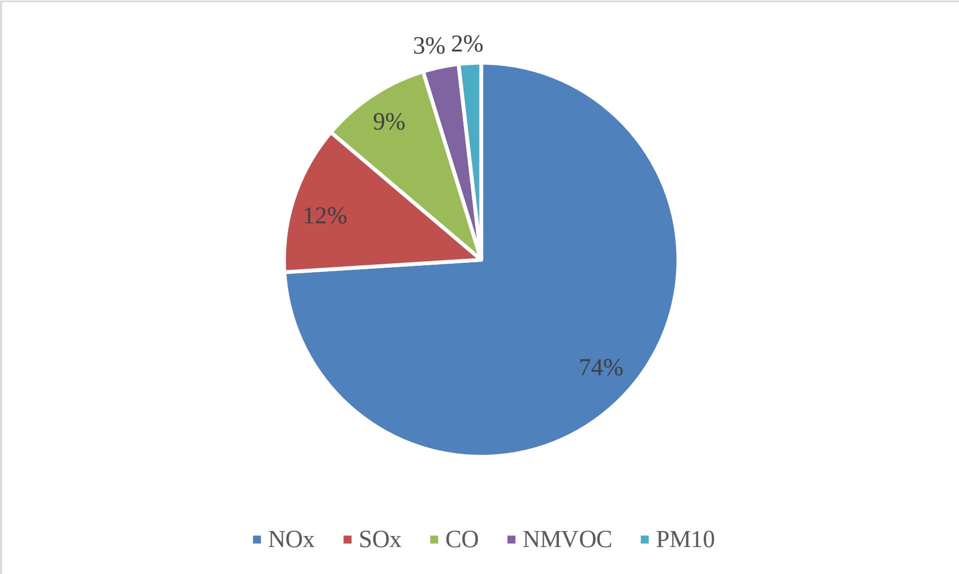

Figure 3.1 : Estimated emissions of open sea voyage (excluding CO_2).

3.1.2 Emission during ice navigation (B)

After the research vessel completes its open sea voyage, it continues ice navigation close to the shore. This cruise is at a distance of 75 nautical miles and the vessel navigates at an average speed of 3 knots due to the ship's cruising and manoeuvrability on the ice. In order to make an emission estimation, the fuel consumption during this voyage must be calculated.

Table 3.3 : Fuel consumption of the vessel during ice navigation.

Parameters	Value
Engine Power (kW)	3600
Engine Load (%)	75
SFOC (g/kWh)	190
Duration (day)	1
C_h (kg)	513
C_f (ton)	12.3

Table 3.4 : Estimated emissions of ice navigation.

Pollutant	EF (kg/ton fuel)	Emission (ton)
CO_2	3206	39.4
NOx	60.6	0.75
SOx	10	0.12
CO	7.4	0.10
NMVOC	2.4	0.03
PM_{10}	1.5	0.02

The ice navigation fuel consumption of the research vessel is shown in Table 3.3. The emission estimation resulting from the fuel burnt on ice navigation is given in Table

3.4. Although the ice navigation phase is slower than the navigation at the open sea course, the emission factors do not change.

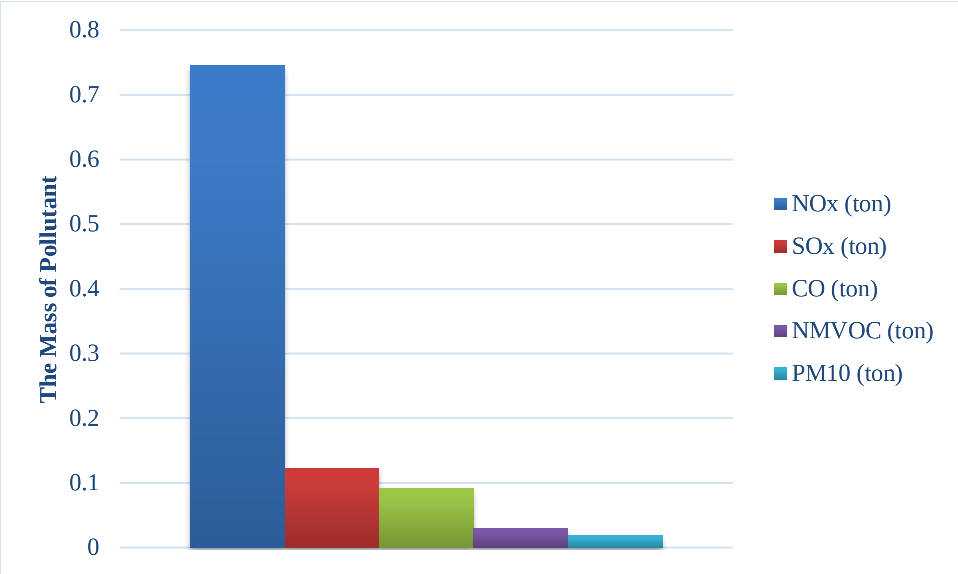

Figure 3.2 : Estimated emissions of ice navigation (excluding CO_2).

In this phase, as in the open sea voyage, it is determined that 98% of all emissions are CO_2 emissions. NOx gas has the highest emission after carbon dioxide. A comparative graph of gases other than CO_2 is given in Figure 3.2. Since there was no change in emission factors, the rates remained the same. However, fuel consumption and emissions are less due to both reduced engine power and shorter travel time.

3.1.3 Emission at anchor or drifting (C)

After completing ice navigation, the research vessel anchors or drifts at a safe point close to the shore. Since there is no navigation at this stage, generators are switched on for energy and heating purposes. In order to make an emission estimation, it is necessary to calculate the fuel consumption occurring at this stage.

Table 3.5 : Fuel consumption of the vessel at anchor or drift.

Parameters	Value
Engine Power (kW)	3600
Engine Load (%)	50
SFOC (g/kWh)	194
Duration (day)	30
C_h (kg)	349.2
C_f (ton)	251.4

Table 3.6 : Estimated emissions of the vessel at anchor or drift.

Pollutant	EF (kg/ton fuel)	Emission (ton)
CO_2	3206	806
NOx	59.7	15
SOx	10	2.5
CO	7.4	1.86
NMVOC	1.8	0.45
PM_{10}	1.4	0.35

The fuel consumption for the standby condition at anchor or drift is calculated in Table 3.5. Emission estimates for this phase are also given in Table 3.6. Emission factors for NOx, NMVOC and PM_{10} values decrease during this period when the research vessel is not navigating. Although the engine is used with a higher performance machine for open sea navigation, the engine is used at half load at this stage.

Although the emission factors of NOx, NMVOC and PM_{10} are lower in this phase, the emission rates are the same as the other factors do not change. It can be seen that 98% of all emissions are composed of CO_2 emissions. A comparative graph of gases other than CO_2 is given in Figure 3.3. However, hourly fuel consumption is lower than in both phases, as the fuel is consumed only for energy and heating while the ship is not navigating.

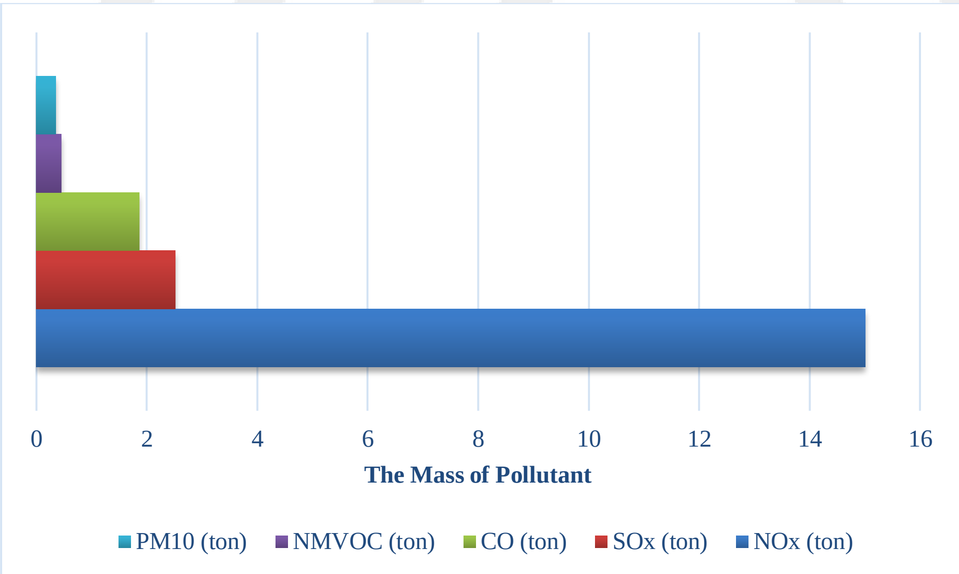

Figure 3.3 : Estimated emissions of the vessel at anchor or drifting (excluding CO_2).

As in navigation conditions, NOx gas has the highest value in the case of staying at anchor or drifting.

3.1.4 Comparison of emissions

Since the emission factors of the gases are constant, proportionally the same results were obtained at each stage. But the phase in which the emissions are the most in mass is the open sea voyage. The engine operating load is at its highest level and the voyage time is quite long on the open sea voyage. Although cruising at a slow speed of 3 knots in ice navigation, the engine power usage of the ship is higher than at 3 knots in the open sea due to environmental factors. Despite the low speed, the emission is high due to the high use of engine power. However, since it is a short distance like one day, the lowest stage in terms of emission mass is the ice navigation phase. In the stay at anchor or drift for the research, the engines act as generators and since they are operating at half load, it is the phase with the lowest hourly consumption. Because the research is planned for 30 days at anchor or drift, the pollutant gas emission mass is higher than the ice navigation phase.

CO_2 emissions are given for each phase in Figure 3.4. 60.5%, 37.6%, and 1.9% of the total CO_2 emissions are open sea navigation, stay at anchor/drift during the research phase and ice navigation, respectively. Figure 3.5 shows the emission of gases other than carbon dioxide for all phases of the expedition.

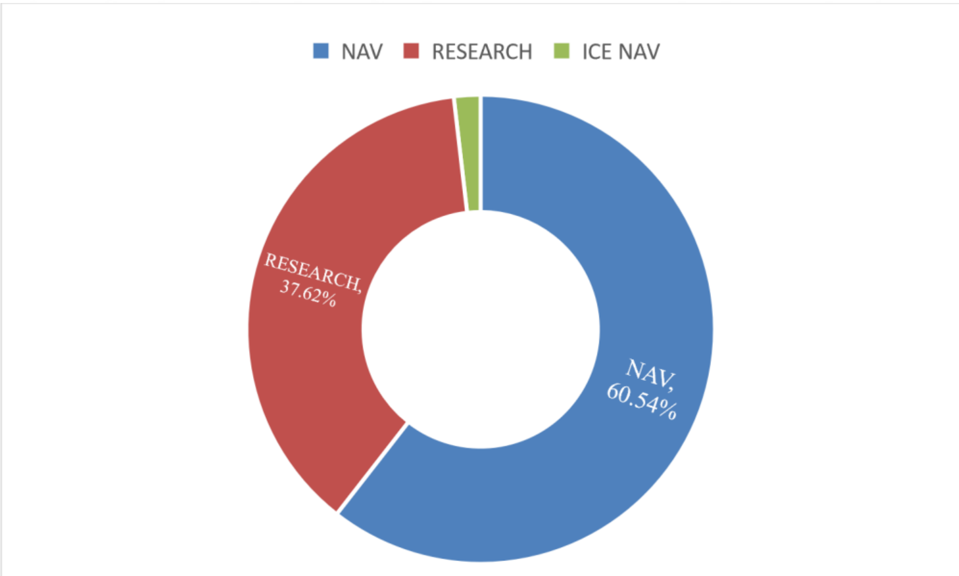

Figure 3.4 : Estimated CO_2 emissions of the vessel for each phase.

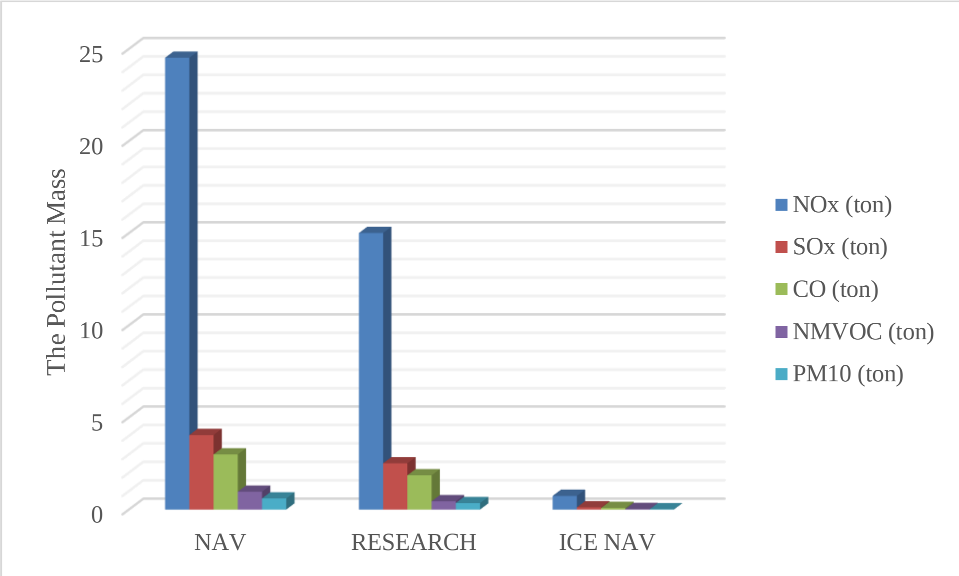

Figure 3.5 : Estimated emissions of the vessel for each phase (excluding CO_2).

3.2 Emission Calculations for Second Scenario

3.2.1 Flight emission (D)

According to the second scenario, the scientists and the crew of the research ship are transported from Europe to Punta Arenas (Chile) by air. The emission estimates are made using the emission factors in Table 2.5 by distance and fuel consumption values in Table 2.3.

Table 3.7 : Estimated emissions of aircraft.

Pollutant	EF_{CRUISE} (kg/ton fuel)	EF_{LTO} (kg/ton fuel)	Total Emission (ton)
CO_2	3150	3160	251
NOx	17	16.4	1.4
CO	5	20	0.51
NMVOC	2.7	6	0.24
SOx	1	1	0.08
N_2O	0.1	0.08	0.008
CH_4	0	0.6	0.005

The emission estimation resulting from the flight is given in Table 3.7. It is determined that the largest share of the emission with a rate of 98% belongs to CO_2 gas.

The graph of the pollutant gases emitted other than carbon dioxide gas is given in Figure 3.6. CH_4 and N_2O are not shown in Figure 3.6 because a negligible amount of gases is released as shown in Table 3.7. Although aircraft do not emit CH_4 during the cruise, this gas is released during landing and take-off. The emission factor for the LTO phase increased for all pollutants except NOx-derived gases.

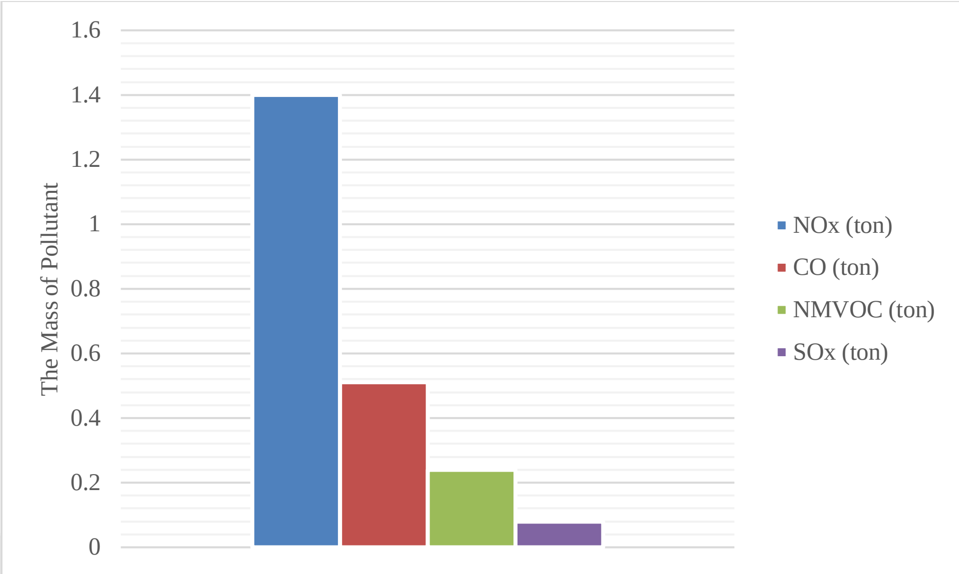

Figure 3.6 : Estimated emissions of aircraft (excluding CO_2).

3.2.2 Emission during open sea voyage (E)

In this scenario, the research vessel departs from Punta Arenas, Chile, to Antarctica. It completes 800 nautical miles at open sea in 2.7 days with an average speed of 12 knots. In order to make an emission estimation, first of all, the fuel consumption occurring during this voyage must be calculated.

Table 3.8 : Fuel consumption of the vessel during the open sea voyage.

Parameters	Value
Engine Power (kW)	3600
Engine Load (%)	85
SFOC (g/kWh)	190
Duration (day)	2.7
C_h (kg)	581.4
C_f (ton)	37.7

Table 3.9 : Estimated emissions of open sea voyage.

Pollutant	EF (kg/ton fuel)	Emission (ton)
CO_2	3206	121
NOx	60.6	2.3
SOx	10	0.38
CO	7.4	0.28
NMVOC	2.4	0.09
PM_{10}	1.5	0.06

The open sea voyage fuel consumption of the research vessel is calculated as stated in equation 2.5 and shown in Table 3.8. The emission estimates as a result of the fuel burnt at the open sea are given in Table 3.9. It is determined that 98% of all emissions are CO_2 emissions. NOx gas has the highest emission after carbon dioxide. A comparative graph of gases other than CO_2 is given in Figure 3.7.

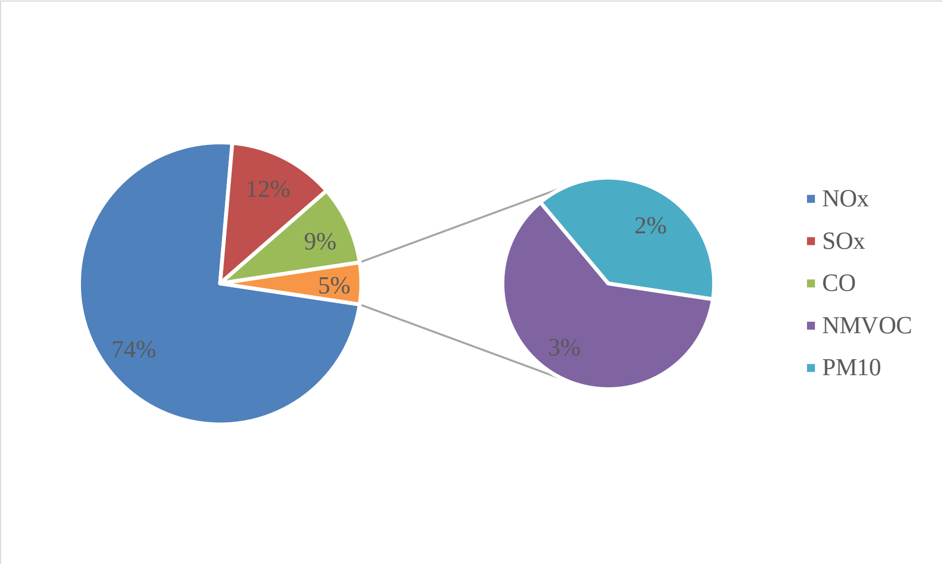

Figure 3.7 : Estimated emissions of open sea voyage (excluding CO_2).

3.2.3 Emission during ice navigation (B)

In this scenario, the research vessel continues its course in the sea ice zone close to the shore after completing its open sea voyage as in the first scenario. This cruise is at a distance of 75 nautical miles and the vessel navigates at an average speed of 3 knots due to the ship's cruising and manoeuvrability on the ice. In order to make an emission estimation, the fuel consumption during this cruise must be calculated.

Table 3.10 : Fuel consumption of the vessel during ice navigation.

Parameters	Value
Engine Power (kW)	3600
Engine Load (%)	75
SFOC (g/kWh)	190
Duration (day)	1
C_h (kg)	513
C_f (ton)	12.3

Table 3.11 : Estimated emissions of ice navigation.

Pollutant	EF (kg/ton fuel)	Emission (ton)
CO_2	3206	39.4
NOx	60.6	0.75
SOx	10	0.12
CO	7.4	0.10
NMVOC	2.4	0.03
PM_{10}	1.5	0.02

Just like in the first scenario, the same consumption and emission occurred here. The ice navigation fuel consumption of the research vessel is shown in Table 3.10. The emission estimates as a result of the fuel burnt in the sea ice zone are given in Table 3.11.

It is determined that 98% of all emissions are CO_2 emissions. NOx gas has the highest emission after carbon dioxide.

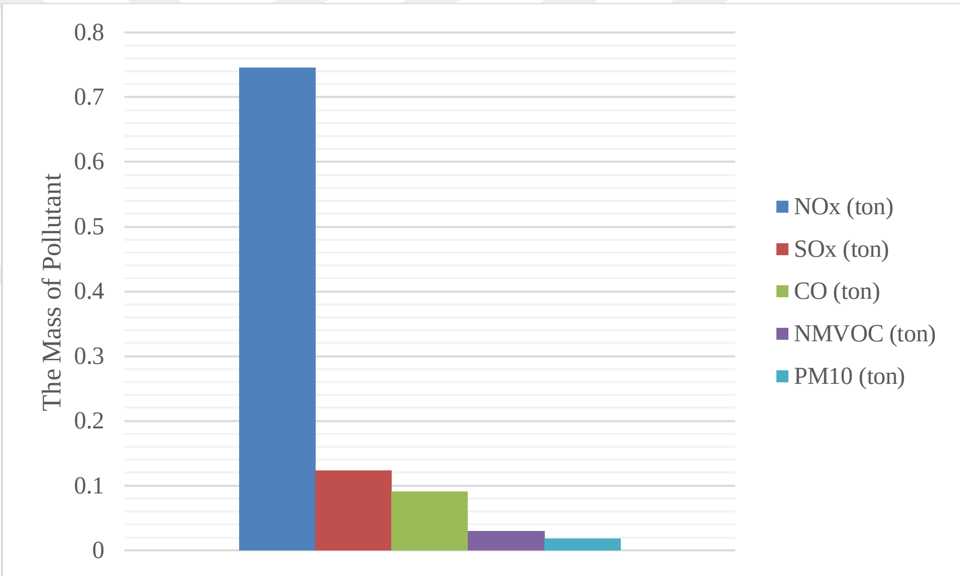

Figure 3.8 : Estimated emissions of ice navigation (excluding CO_2).

Figure 3.8 shows the comparative graph of gases other than CO_2. Since there is no change in emission factors, the rates remain the same. However, fuel consumption and emissions are less due to both reduced engine power and shorter travel time.

3.2.4 Emission at anchor or drifting (C)

The research vessel anchors or drifts at a safe point close to the shore after completing the ice navigation stage. Engines are used as generators for energy and heating purposes. In order to make an emission estimation, it is necessary to calculate the fuel consumption occurring at this stage.

Table 3.12 : Fuel consumption of the vessel at anchor or drift.

Parameters	Value
Engine Power (kW)	3600
Engine Load (%)	50
SFOC (g/kWh)	194
Duration (day)	30
C_h (kg)	349.2
C_f (ton)	251.4

As in the first scenario, the same consumption and emission took place here. The fuel consumption for the standby condition at anchor or drift is calculated in Table 3.12.

Table 3.13 : Estimated emissions of the vessel at anchor or drift.

Pollutant	EF (kg/ton fuel)	Emission (ton)
CO_2	3206	806
NOx	59.7	15
SOx	10	2.5
CO	7.4	1.86
NMVOC	1.8	0.45
PM_{10}	1.4	0.35

The emission estimates for this phase are also given in Table 3.13. The emission factors decrease during the standby phase for NOx, NMVOC and PM_{10} values.

Although the emission factors of NOx, NMVOC and PM_{10} are lower in this phase, the emission rates are the same as the other factors do not change. It can be seen that 98% of all emissions are composed of CO_2 emissions. Figure 3.9 shows the comparative graph of gases other than CO_2. The hourly fuel consumption is lower than the other three phases, as there is no other energy requirement other than electricity and heating. However, total consumption and emissions are highest at anchor or drift in this scenario.

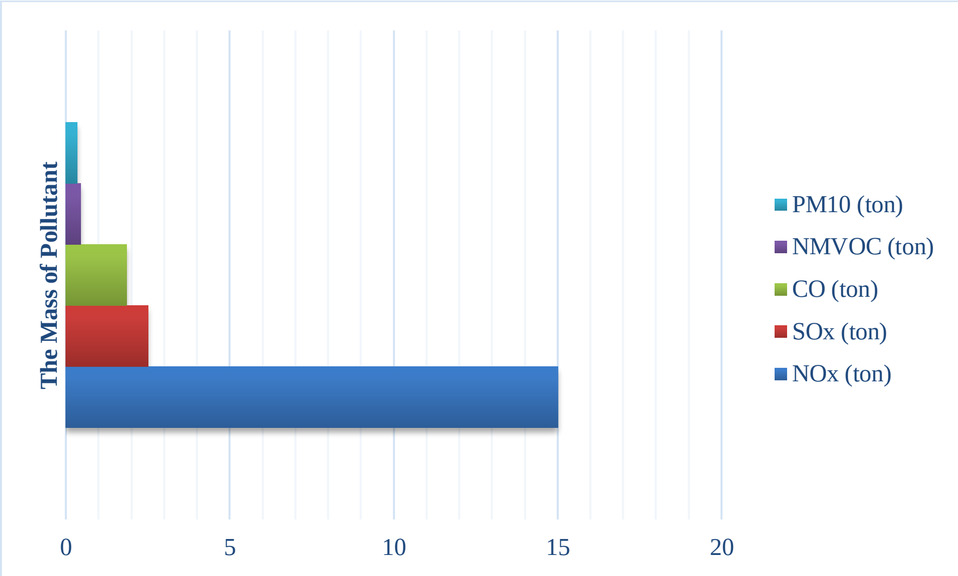

Figure 3.9 : Estimated emissions of the vessel at anchor or drifting (excluding CO_2).

As in the navigation stage, NOx gas has the highest value at anchor or in drifting conditions.

3.2.5 Comparison of emissions

In this scenario, there is air transportation in addition to the first scenario. Since the aircraft emission factors differ from ship emission factors, the emission of the gases result is proportionally different from shipping emissions. In addition, CH_4 gas emerges in the LTO states of aircraft. This gas is not emitted by ships. PM_{10} is not observed in flight emissions either.

During the stay at anchor or drift for the research, the engines act as generators and since they operate at half load, it is the phase with the lowest hourly consumption. However, since the research is planned for 30 days, the mass of pollutant gas emissions is the highest in comparison with the other stages. Although the engine operating load is much less than for navigation at open sea and on sea ice areas, stay time at anchor or drift is quite long.

The fuel consumption and emissions resulting from the flight are higher than the navigation phases. Fuel consumption and emissions are lower in the open sea voyage due to shorter distance and cruising time in comparison with flight and staying at anchor/drift.

Although navigation is performed at a slow speed on sea ice areas, the engine power load of the ship is higher than at 3 knots in the open sea due to the effect of environmental factors. Despite the low speed, the emission is high due to the high load of the engine. However, since it is a short cruise like one day, the lowest stage in terms of emission mass is the ice navigation phase.

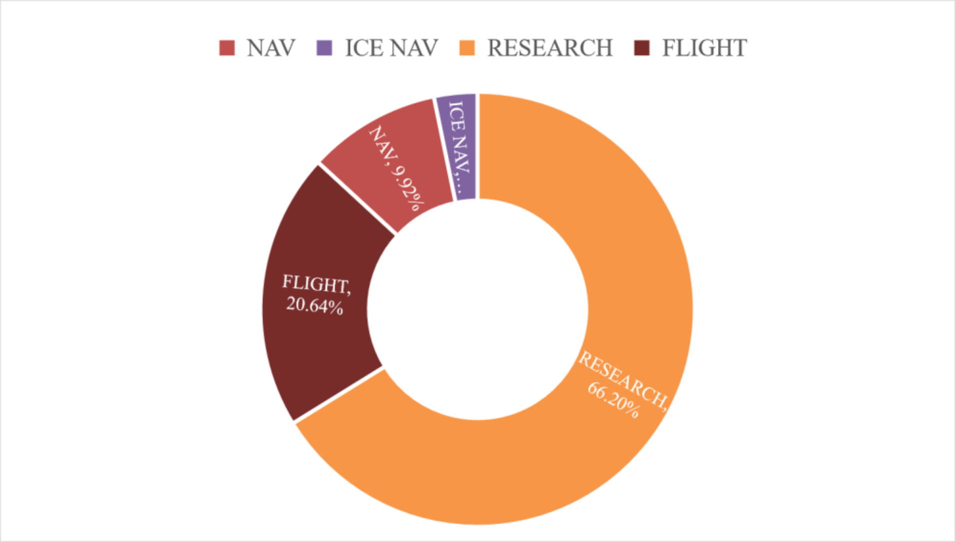

Figure 3.10 : Estimated emissions of the vessel for each phase.

CO_2 emissions are given for each phase in Figure 3.10. 66.2%, 20.6%, 9.9%, and 3.3% of the total CO_2 emissions are staying at anchor/drift during the research phase, flight, open sea voyage and ice navigation, respectively. Figure 3.11 shows the emission of gases other than carbon dioxide for all stages of the voyage.

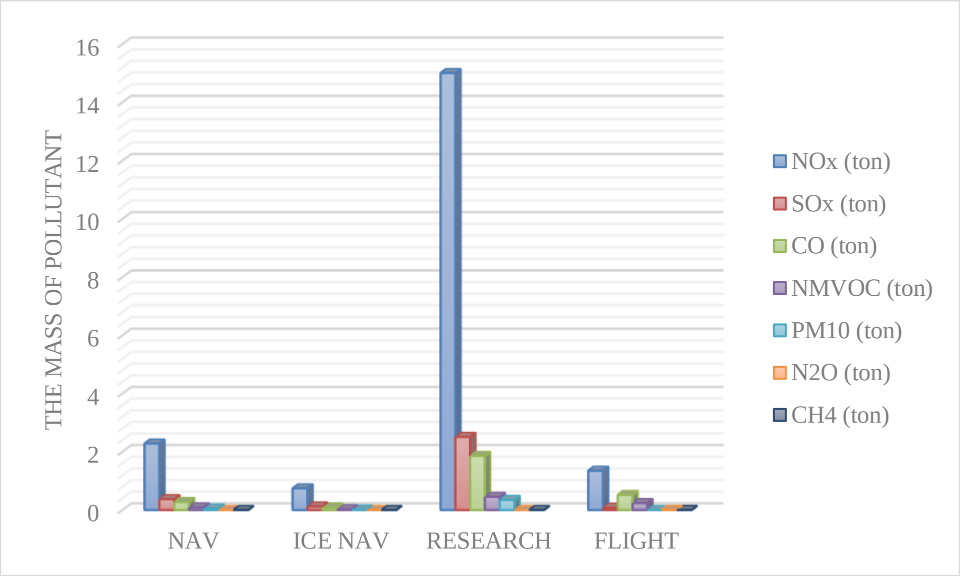

Figure 3.11 : Estimated emissions of the vessel for each phase (excluding CO_2).

3.3 Operations on Vessel During Research Phase

In addition to the carbon emission caused by the fuel used for energy and heating in the standby phase at anchor or drift of the research vessel, the emissions resulting from the work activities of the scientists are given in this section.

3.3.1 Emission of zodiac boat operation

During the research, zodiac boats are used to land ashore. In order to calculate the emission resulting from the boat operation, the fuel consumption of the boat must be known.

Table 3.14 : Fuel consumption of zodiac boat.

Parameters	Value
Motor Power (hp)	115
Engine Load (RPM)	3500
SFOC (liter/hour)	13.2
Duration (hour)	30
Total Cons. (ton)	0.3

A total of 30 hours of boat usage is stated in 30 days with 1 hour of operation per day. Total fuel consumption is given in Table 3.14. Since the fuel is gasoline, different from the ship, the emission factors are also different. Differences in burning times and temperatures change emission values. Emission values and the amount of gas released are given in Table 3.15.

Table 3.15 : Estimated emissions of zodiac boat operations.

Pollutant	EF (kg/ton fuel)	Emission (kg)
CO_2	3256	950
CO	348	102
NMVOC	29.2	8.5
NOx	25.8	7.5
TSP	0.188	0.05
PM_{10}	0.188	0.05
$PM_{2,5}$	0.188	0.05
NH_3	0.005	0.001

It is determined that 89% of all emissions are composed of CO_2. In addition, 10% of the remaining emissions consist of CO. CO_2 and CO gas emissions are the most in comparison with other gases. A comparative graph of the gases released other than CO_2 and CO gas is given in Figure 3.12.

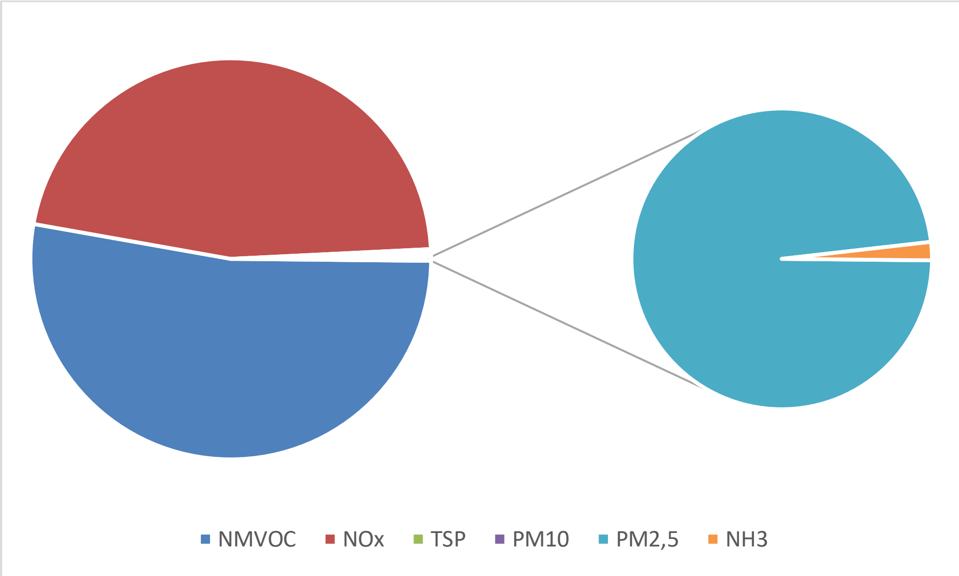

Figure 3.12 : Estimated emissions of boat operations (excluding CO_2 and CO).

Since the fuel is different, the emission factors and the released gases also change. Total suspended particles (TSP) and NH_3 were not observed at any other stage. Considering the amount of emissions released at all stages in both scenarios, it is understood that the emissions from boat use have a very low impact.

3.3.2 Emission of helicopter operation

8 flights, which will take 4 hours in total, are determined in both scenarios. Since the fuel consumption and consumption in LTO phases are different from the cruise, they are calculated separately.

The total fuel consumption for 8 flights is calculated as 262.4 kg for LTO phases and 814 kg for cruising. It is determined that the fuel consumed in the LTO process is even more than an hour's fuel consumption.

Table 3.16 : Estimated emissions of helicopter operations.

Pollutant	Emission LTO (kg)	Emission Cruise (kg)
CO_2	827	2564
CO	10.1	9.1
HC	7.7	7.3
NOx	1.0	4.2
PM Non-Volatile	0.039	0.14

The total LTO for 8 flights and the amount of emissions as a result of the cruise are given in Table 3.16. It is stated that the amount of emissions is higher in parallel with the high amount of fuel consumed in the LTO process.

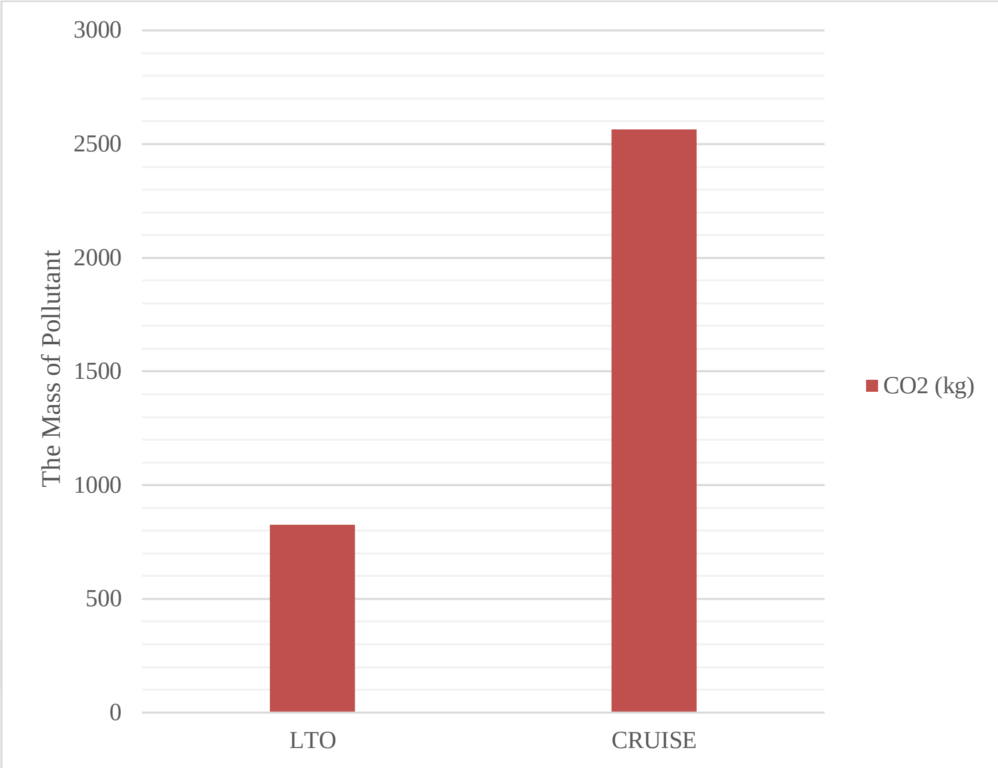

Figure 3.13 : Estimated CO_2 emissions of helicopter operations.

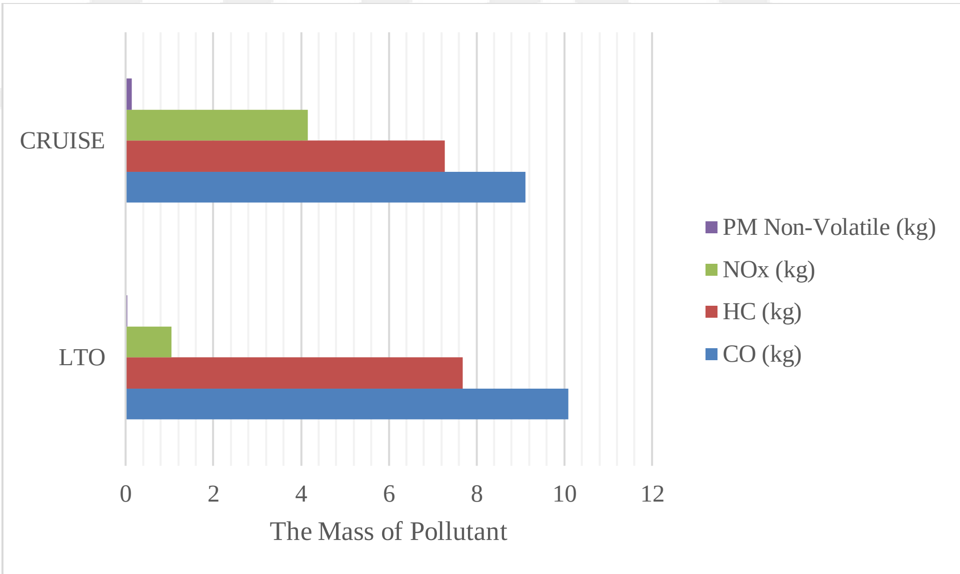

Figure 3.14 : Estimated emissions of helicopter operations (excluding CO_2).

Figure 3.13 shows the total CO_2 emissions in the helicopter operation. The carbon emission factor in the cruise stage is less than in the LTO process. Emissions of gases other than CO_2 are given in Figure 3.14. The cruise values of CO and HC emissions in the LTO phase are almost equal. It is observed that there is more emission in the LTO stage, as in the CO_2 emission.

3.4 Comparison of Scenarios

3.4.1 Carbon emissions

In the first scenario, all stages of the expedition are carried out entirely by sea, while in the second scenario, the expedition is carried out by sea integrated with airlines. The open sea voyage is the most polluting phase in the first scenario, as it takes a very long distance and a lot of time. In the second scenario, since the open sea navigation is made using the alternative of the airline, the emission is dramatically less than that of the first scenario. In order to determine the environmental impact of the expeditions in both scenarios, the same route and research duration are determined. For this reason, the estimated CO_2 emissions during ice navigation and staying at anchor or drift are the same.

Table 3.17 : Estimated CO_2 emission of scenarios for each phase.

Phase	1st Scenario (ton)	2nd Scenario (ton)
Navigation	1297	121
Research	806	806
Ice Navigation	39.4	39.4
Flight	0	251
Total	2142.4	1217.4

Estimated CO_2 gas emissions in Table 3.17 are given as mass for all phases of both scenarios. Even if the flight emission in the second scenario is added to the emission of the open sea navigation in the second scenario, the emission of navigation at the open sea value in the first scenario cannot be reached.

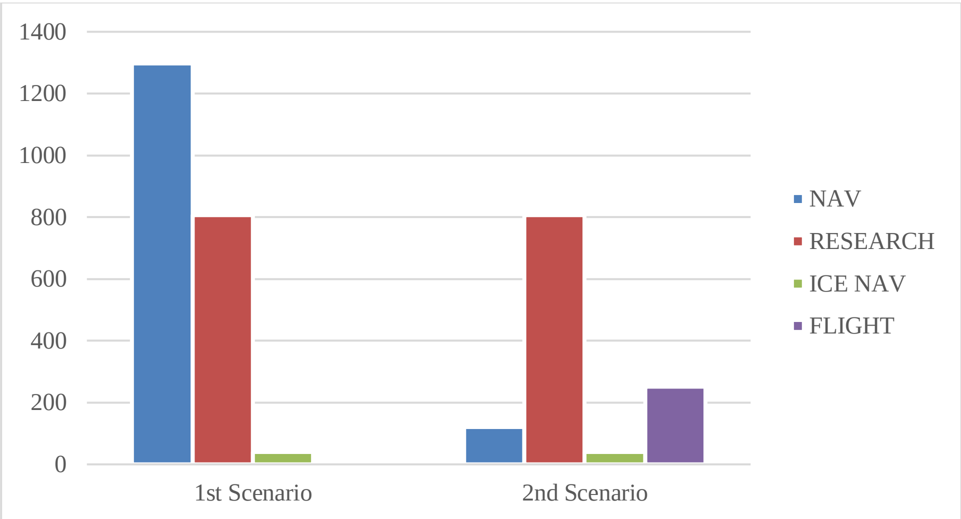

Figure 3.15 : Estimated CO_2 emission of scenarios for each phase.

The CO_2 emissions of each phase of both scenarios are given in Figure 3.15. Organizing an integrated flight to Antarctica is more environmentally friendly than arriving directly from Europe by ship.

3.4.2 Emissions other than CO_2

Since there is no flight emission in the first scenario, CH_4 gas is not released. All gases except CO_2 released are given in Table 3.18, according to the phase and scenario. N_2O gas is calculated separately for flight emissions. N_2O emission value is included in NOx for emissions originating from the ship. For this reason, the only gas that is not common in the two scenarios is CH_4. PM_{10} is only released as a result of ship navigation. Since the emission values in boat and helicopter operations have a very low impact, they are not included in Table 3.18.

Table 3.18 : Estimated emission of scenarios for each phase (excluding CO_2).

Phase & Scenario	NOx (ton)	SOx (ton)	CO (ton)	NMVOC (ton)	PM_{10} (ton)	N_2O (ton)	CH_4 (ton)
Nav-1	24.522	4.046	2.994	0.971	0.607	0	0
Nav-2	2.283	0.376	0.278	0.090	0.056	0	0
Ice Nav-1	0.746	0.123	0.091	0.029	0.018	0	0
Ice Nav-2	0.746	0.123	0.091	0.029	0.018	0	0
Research-1	15.010	2.514	1.860	0.452	0.352	0	0
Research-2	15.010	2.514	1.860	0.452	0.352	0	0
Flight-1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Flight-2	1.351	0.079	0.518	0.241	0	0.008	0.005

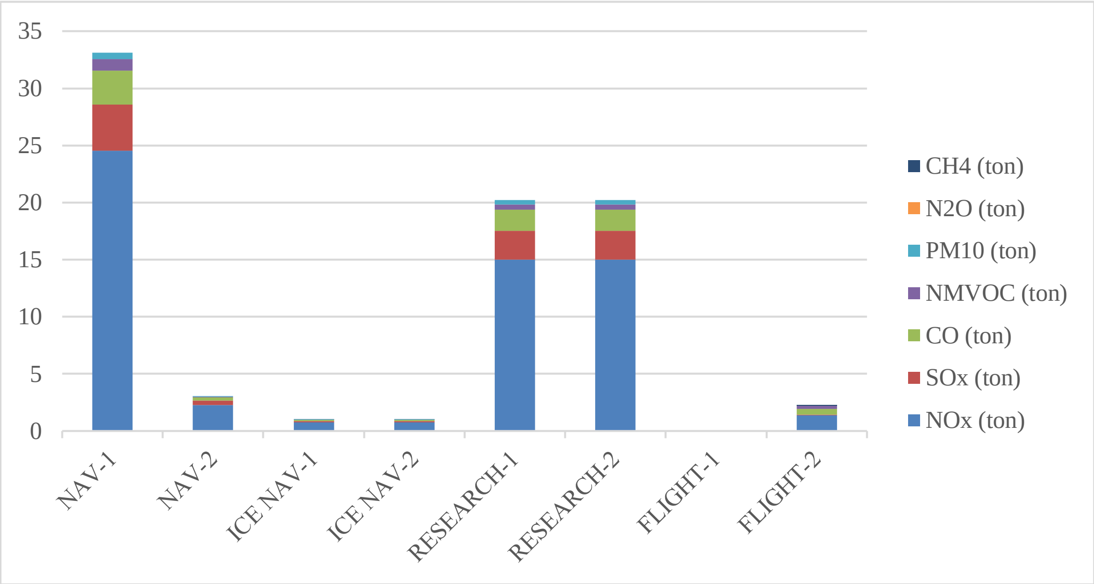

Figure 3.16 : Estimated emission of scenarios for each phase (excluding CO_2).

Figure 3.16 shows the comparative graph of all the phases that took place in the two scenarios. As with the CO_2 emission, the emissions of other gases are exactly the same as those of the ice navigation and staying at anchor or drift. In both scenarios, expeditions are organized to the same region and the research times are determined equally. Therefore, the estimated gas emissions and the amount of fuel consumed during the ice navigation and staying at anchor or drift are the same.

3.4.3 Summary of scenarios

Emissions in the scenarios were calculated separately for each stage and compared with each other. The scenarios were assessed by categorizing them as carbon dioxide and other gases in terms of their phases. In this section, the emission at each coded stage for all polluting gases and the total emission in both scenarios are prepared as a summary table.

Table 3.19 : Emissions of all stages of scenarios.

Pollutant	A (ton)	B (ton)	C (ton)	D (ton)	E (ton)
CO_2	1297	39.5	806	251	121
NOx	24.5	0.75	15.0	1.4	2.3
SOx	4.0	0.12	2.5	0.08	0.38
CO	3.0	0.09	1.9	0.51	0.28
NMVOC	0.97	0.03	0.45	0.24	0.09
PM_{10}	0.61	0.02	0.35	0.00	0.06
N_2O	-	-	-	0.008	-
CH_4	-	-	-	0.005	-

Table 3.20 : Emissions of scenarios.

Pollutant	1st Scenario (ton)	2nd Scenario (ton)
CO_2	2143	1218
NOx	40.2	19.4
SOx	6.7	3.1
CO	4.9	2.7
NMVOC	1.5	0.81
PM_{10}	1.0	0.43
N_2O	-	0.008
CH_4	-	0.005

Emissions at all coded stages are given in Table 3.19. The total emissions for the scenarios are given in Table 3.20.

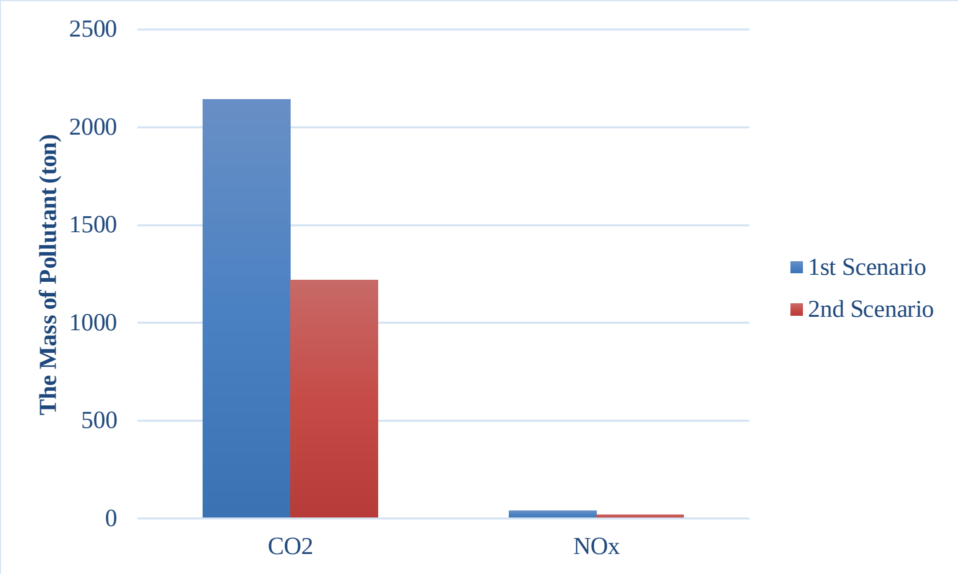

Figure 3.17 : Estimated carbon emission of scenarios.

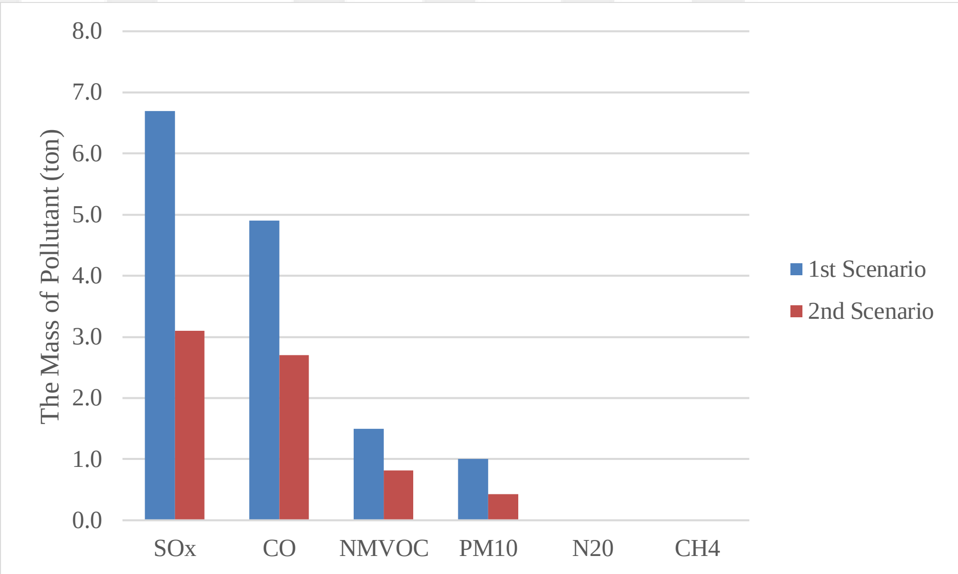

Figure 3.18 : Estimated emissions of scenarios (excluding CO_2).

Figure 3.17 shows CO_2 and NOx-derived gases released in both scenarios. Figure 3.18 has a comparative graph of pollutants other than CO_2 and nitrogen-derived gases for both scenarios. As can be clearly seen in the summary tables and figures, the second scenario is the most environmentally friendly. Both carbon and nitrogen-derived gases are minimized in this scenario.

3.5 Alternative Technologies and Methods for Reducing Emissions

The basic principle for reducing carbon emissions is to reduce fuel consumption. The less fossil fuels are consumed, the less carbon dioxide is produced. If distances and travel time can be shortened with route optimization, there will be a reduction in carbon emissions. For example, if expeditions are started from countries close to the Antarctic continent, fuel savings will be realized as the cruising distance will be shortened. The benefit of this is demonstrated by the values obtained in the airline integration in the second scenario.

The expeditionary research vessel can be selected with lower engine power. Smaller research ships can be used depending on the needs of the research to be carried out and the number of scientists. A smaller ship may save fuel, so there may be a noticeable reduction in carbon emissions. However, there is definitely a limit to the minimum size of the research ship according to the scope and needs of the expedition. It is obvious that very small boats cannot cruise safely due to the harsh weather of the southern ocean. By the same logic, a ship with an overly small engine cannot also struggle with extreme weather conditions (de Waal et al, 2018). Along with route optimization, the speed reduction method will also reduce the emission of the research vessel. The main factor to be considered when reducing the speed is the optimum RPM of the engine. Long-term operation of the engine at speeds that will prevent complete combustion of the fuel will cause an increase in BC and HC emissions.

Alternative fuels will also reduce the emission rate. Although not common yet, methanol and LNG-powered vessels are available. Methane in LNG is the fuel with the lowest carbon level. Due to the purification of sulphur and its derivatives during LNG production, SOx emission does not occur. Compared to other marine fuels, the emission of nitrogen-derived gases is lower. Similarly, methanol is a sulphur-free fuel with low carbon content. The most striking feature of methanol is that it can be used as a fuel by making it usable in diesel engines. This offers less emission possibilities without creating any machinery installation costs. For this reason, engines working with LNG and methanol type fuels will cause less emissions than diesel engines. (Ejder, 2020). However, the ship's diesel engines operate with a pressure ignition system. Since the structure of methanol is similar to gasoline, it is a suitable fuel for engines with spark ignition systems. In diesel-powered vessels, methanol is applicable for the pressure ignition system with additives. Nonetheless, because these additives are highly toxic, it is recommended to use them with different technologies. In addition, it is more convenient for use in diesel engines with dual fuel systems. The dual-fuel systems also have their own obstacles. The biggest disadvantage in the dual fuel systems is that the methanol content used is low because diesel and methanol are not homogeneously mixed during ignition. Therefore, systems are preferred with the injection of methanol and diesel into cylinders separately (Dierickx et al, 2018).

Hybrid propulsion systems dramatically reduce carbon emissions. Shipping emissions will decrease as hybrid propulsion systems become more common. Hybrid ships meet the energy needs of the ship by using fuel cell systems or battery systems. In fuel cell systems, hydrogen is used as the main energy source. Hydrogen is stored in these batteries in various ways. In this way, it greatly reduces CO_2, SOx, and NOx emissions when used as auxiliary engines with main diesel engines. If an electrical propulsion system is used with batteries, emissions become zero. Battery systems used as a hybrid with a diesel engine greatly reduce CO_2, SOx, and NOx emissions (Ejder, 2020). As fuel cells and battery technologies develop, zero-emissions will become possible for shipping.

In addition to the need for electricity in cold regions, the research vessel also requires a serious amount of energy due to heating. Cogeneration systems generate heat from the waste gas of the ship's funnel. This system reduces carbon emissions and increases the efficiency of the research vessel in terms of energy consumption. Combined heat and power (CHP) technologies are cost-effective systems and simultaneously produce electricity and heat with single fuel. Engines integrated with the CHP system can be used according to changing electrical and thermal heat requirements (Yang, 2016). High-efficient trigeneration systems also generate cold in addition to electricity and heat. However, since the environment in Antarctica is cold enough, there is no need for a trigeneration system.

Exhaust gas cleaning system (scrubber), selective catalytic reduction system (SCR) and exhaust gas recirculation system (EGR) are available for ships in order to reduce NOx and SOx emissions which lead to increase serious climate changes such as ozone depletion. In scrubber technology, before the exhaust gas is released, it is cleaned of sulphur by washing. By using the catalyst and reducing agent in the SCR system, the nitrogen ratio in the exhaust gas is significantly reduced. The EGR system also reduces the combustion temperature of the fuel in the engine and ensures that less NOx is released. In this way, there is a decrease in nitrogen emissions (Lamas & Rodriguez, 2012).

As the cruising duration of the research ships increases in the Antarctic expeditions, the carbon emission becomes higher. The most CO_2 emissions are released in the first scenario, as the research ship is the only vehicle used in all phases of the expedition. In the second scenario, it was determined that there was a noticeable reduction in emissions with the airline integration. The main reason for the emission is to obtain energy by burning fossil fuels. For this reason, it was determined that the emission increases as the travel time of the vehicles used in the expedition increases. In the light of this information, it was determined that emissions are mostly in the logistics part of the expedition in the first scenario since the cruising time is much longer in the first scenario than in the second scenario. It was determined that the highest emission stage is the research phase while staying at anchor or drifting where fuel is used for energy and heating needs.

Emissions of nitrogen and sulphur-derived gases were determined as the pollutant gases that emerged at the highest rate after carbon emission. In the first scenario, it was assessed that more than the second scenario was released due to the use of only ships in the expedition. Apart from these, since the CH_4 gas originates from the aircraft, it only occurred at a negligible low level in the second scenario. NMVOC, PM_{10} and CO emissions were also higher in the first scenario than in the second scenario. In this regard, it is clearly seen that the high amount of fuel used is primarily responsible for emissions. In both scenarios, the use of zodiac boats and helicopters is envisaged for research carried out while staying at anchor or drifting. The fuel consumption and emissions of these vehicles, especially from the use of the zodiac boat, are at a negligible level. In practice, emissions from helicopters are also not very high compared to other phases of the voyage, if the use of helicopters does not exceed those planned in the scenarios. However, it was observed that as an aircraft, helicopters can cause a noticeable increase in emissions as a result of long-term and frequent use.

The most basic method for minimizing the negative effects of Antarctic expeditions on the environment will be to reduce fuel consumption. For this, research ships that cause the least emissions should be preferred in accordance with the regional conditions and the needs of scientific studies. In addition, reduction in emission rates can be achieved with route optimizations and low-speed applications. Considering the cold climate of the region, the energy required for heating in the research vessel is also seen as a factor that will increase fuel consumption. Although it is not mentioned in this thesis, since autonomous ships are currently in the testing phase and are not required for studies on Antarctica, such ships can be used to collect data by remote control in hazardous areas in the Southern Ocean.

4. CONCLUSION

The melting of glaciers and sea ice around the world due to climate change is one of the biggest environmental disasters known. In order to reduce the consequences of climate change, it is necessary to eliminate or reduce the factors that trigger climate change and the resulting global warming. The greenhouse gases cover the world like a blanket, preventing the existing heat from leaving the world and causing temperatures to increase. Likewise, the decrease in the albedo effect causes a decrease in heat reflection. Because of increasing black carbon emission in polar regions, the mass of glaciers and sea ice melt fast and this greatly limits the albedo effect. Since the research carried out in Antarctica are necessary for data collection, expeditions are regularly made here. Studies carried out so far in Antarctica have provided data to prove climate change. In particular, studies on ice cores obtained by drilling provide humanity with an idea about the climate in the past. The main reason for this is that no indigenous population exists in Antarctica.

Since commercial vessels make frequent voyages to transport cargo or passengers between ports, studies in the literature focus on the effects of ship emissions on climate change and the port environment. In the literature, route optimization and economic speed applications provide fuel savings and thus reduce emissions from ships. As a result of the scenarios prepared within the scope of the study, it was determined that the first scenario caused more harm to the environment than the second scenario. The long-term navigation of the research vessel causes more fuel consumption and increases the emission. As a result of optimizing the voyage route, it’s determined a decrease in fuel consumption and emissions. The second scenario has been determined as the most logical and environmentally friendly scenario for countries far from Antarctica. Since no changes were made in the scenarios regarding the research vessel speed, an assumption for speed optimization was not possible. However, the speed of the research vessel selected for the scenario was determined at a moderate level suitable for ice navigation and extreme meteorological conditions. In the literature, the emissions from the vessels staying for their operations in the port area and inland seas were examined and found to have a significant impact on the environment, as well as the environmental effects of the cruise vessels making touristic voyages to Antarctica and the vessels engaged in fishing activities in the Southern Ocean. It was determined that a research vessel staying at anchor or drifting in Antarctica during the research phase was similar. These results agree with the studies in the literature.

In both scenarios, CO_2 was emitted the most, followed by nitrogen and sulphur-derived gases. To reduce carbon emissions, fuel consumption should be reduced and alternative fuel systems should be preferred. Modern filtration technologies can be used to reduce the emission of nitrogen and sulphur-derived gases. In order to take the study further, different logistics methods can be developed by examining the expeditions to the region in more detail. Thus, polluted gas emissions can be reduced below the values determined in these scenarios. Calculations made with the scenarios prepared within the scope of the thesis are exemplary for research ships carrying out Antarctic expeditions. It is thought that the result obtained in this study will encourage the application of different logistics methods in new expeditions to the region in the future.

REFERENCES

AARI (2021). *AARI-NIC-NMI pilot project on integrated sea ice analysis for Antarctic waters*. Retrieved December, 26, 2021 from: http://ice.aari.aq/antice/2021/

Acker, J., Williams, R., Chiu, L., Ardanuy, P., Miller, S., Schueler, C., Vachon, P. W., & Manore, M. (2014). Remote Sensing from Satellites, *Reference Module in Earth Systems and Environmental Sciences*, *2003*, 161-202.

Acomi, N., & Acomi, O. C. (2014). Improving the voyage energy efficiency by using EEOI. *Procedia – Social and Behavioral Sciences*, *138*, 531–536.

Bender, N. A., Crosbie, K., & Lynch, H. J. (2016). Patterns of tourism in the Antarctic Peninsula region: a 20-year analysis. *Antarctic Science*, *28*, 194–203.

Bharti, P. K. & Gajananda, Kh. (2013). Environmental monitoring and assessment in Antarctica, In: Environmental Health and Problems, *Discovery Publishing House*, 178-186.

Bharti, P. K. (2015). Solid Waste Management at Indian Research Stations over East Antarctica, In: Waste Disposal and Management, *Discovery Publishing House*, 1-17.

Braun, C., Mustafa, O., Nordt, A., Pfeiffer, S., & Peter, H. U. (2012). Environmental monitoring and management proposals for the Fildes Region, King George Island, Antarctica. *Polar Research*, *31*.

Cefic-ECTA (2011). Guidelines for Measuring and Managing CO_2, *Emission from Freight Transport Operations*, Issue 1.

Chang, C. C., & Wang, C. M. (2012). Evaluating the effects of green port policy: case study of Kaohsiung harbor in Taiwan. *Transportation Research Part D: Transport and Environment*, *17* (3), 185–189.

Chang, C. C., & Jhang, C. W. (2016). Reducing speed and fuel transfer of the green flag incentive program in Kaohsiung port Taiwan. *Transportation Research Part D: Transport and Environment*, *46*, 1–10.

Chang, C. C., & Wang, C. M. (2013). Energy conservation for international dry bulk carrier via vessel speed reduction. *Energy Policy*, *59*, 710–715.

Chou, C. C., Hsu, H. P., Wang, C. N., & Yang, T. L. (2021). Analysis of energy efficiencies of in-port ferries and island passenger-ships and improvement policies to reduce CO_2 emissions, *Marine Pollution Bulletin*, *172*.

Chown, S. L., Lee, J. E., Hughes, K. A., Barnes, J., Barrett, P. J., ... Wall, D. H. (2012a). Challenges to the future conservation of the Antarctic. *Science 337*, 158–159.

Chown, S. L., Huiskes, A. H. L., Gremmen, N. J. M., Lee, J. E., Terauds, A., ….. Bergstrom, D. M. (2012b). Continent-wide risk assessment for the establishment of nonindigenous species in Antarctica. *Proceedings of the National Academy of Sciences*, *109*, 4938–4943.

COMNAP (2017). *COMNAP Antarctic Station Catalogue*. Retrieved December, 15, 2021 from: https://www.comnap.aq/Members/Shared%20Documents/COMNAP_Antarctic_Station_Catalogue.pdf.

Constable, A. J., Melbourne-Thomas, J., Corney, S. P., Arrigo, K. R., ….. Ziegler, P. (2014). Climate change and Southern Ocean ecosystems I: how changes in physical habitats directly affect marine biota. *Global Change Biology*, *20*, 3004–3025.

Corbett, J. J., & Fischbeck, P. S. (1997). Emissions from ships. *Science*, *278(5339)*, 823–824.

Cosofret, D., Bunea, M., & Popa, C. (2016). The Computing Methods for CO_2 Emissions In Maritime Transports, *International Conference Knowledge-Based Organization*, *22*, 3.

de Waal R. J. O., Bekker A., & Heyns, P. S. (2018). Indirect load case estimation for propeller-ice moments from shaft line torque measurements, *Cold Regions Science and Technology*, *151*, 237-248.

Dierickx J., Beyen J., Block R., Hamrouni M., Huyskens P., Meichelböck C., & Verhelst S. (2018). Strategies for introducing methanol as an alternative fuel for shipping, *Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, Vienna, Austria.*

Ejder, E. (2020). *Gemi kaynakli egzoz emisyonları azaltma yöntemlerinin karşılaştırmalı analizi* (Yüksek Lisans Tezi). İstanbul Teknik Üniversitesi Fen Bilimleri Enstitüsü, İSTANBUL.

EMEP/EEA (2019). *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019*. Retrieved December, 15, 2021 from: https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/download.

Farman, J. C., Gardiner, B. G., & Shanklin, J. D. (1985). Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interaction. *Nature*, *315* (6016), 207-210.

Farreny, R., Oliver-Solà, J., Lamers, M., Amelung, B., Gabarrell, X., Rieradevall, J., Boada, M., & Benayas, J. (2011). Carbon dioxide emissions of Antarctic tourism. *Antarctic Science*, *23* (6), 556-566.

Hara, K., Sudo, K., Ohnishi, T., Osada, K., Yabuki, M., Shiobara, M., & Yamanouchi, T. (2019). Seasonal features and origins of carbonaceous aerosols at Syowa Station, coastal Antarctica. *Atmospheric Chemistry and Physics*, *19*, 7817–7837.

Hughes, K. A., Fretwell, P., Rae, J., Holmes, K., & Fleming, A. (2011). Untouched Antarctica: mapping a finite and diminishing environmental resource. *Antarctic Science*, *23*, 537–548.

Hughes, K. A., & Convey, P. (2020). Implications of the COVID-19 pandemic for Antarctica. *Antarctic Science, 32*, 426–439.

Hughes, K. A., Convey, P., & Turner, J. (2021). Developing resilience to climate change impacts in Antarctica: An evaluation of Antarctic Treaty System protected area policy. *Environmental Science & Policy*, *124*, 12-22.

IAATO (2017). *Tourism Statistics*. Retrieved December, 16, 2021 from: https://iaato.org/en_GB/tourism-statistics.

IAATO (2019). IAATO overview of Antarctic tourism: 2018–19 season and preliminary estimates for 2019–20 Season. Information Paper 140. *In Antarctic Treaty Consultative Meeting XLII*. Prague, Czech Republic, 27–28 June 2019.

ICAO (2018). *ICAO Carbon Emissions Calculator Methodology Version 11*, Retrieved January, 13, 2021 from: https://www.icao.int/environmental-protection/CarbonOffset/Documents/Methodology%20ICAO%20Carbon%20Calculator_v11-2018.pdf

IMO (2008). *Resolution MEPC 177 (58), Amendments to the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines (NOx Technical Code 2008)* IMO London. Retrieved December, 26, 2021 from: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.177(58).pdf.

IMO (2012). *Resolution MEPC.212(63) Guidelines on the method of calculation of the attained energy efficiency design index (EEDI) for the new ships, MEPC 63/23*, IMO London. Retrieved December, 26, 2021 from: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.212(63).pdf

IPCC (1996). *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories: Reference Manual*, p 1.98.

IPCC (2021). *Climate Change 2021 The Physical Science Basis*. Retrieved December, 16, 2021 from: https://www.ipcc.ch/report/ar6/wg1/#FullReport

Lack, D. A., Moosmüller, H., McMeeking, G. R., Chakrabarty, R. K., & Baumgardner, D. (2014). Characterizing elemental, equivalent black, and refractory black carbon aerosol particles: a review of techniques, their limitations and uncertainties. *Analytical and Bioanalytical Chemistry, 406*, 99–122.

Lamas, M. I. & Rodriguez, C. G. (2012). Emissions from Marine Engines and NOx Reduction Methods. *Journal of Maritime Research*, *9*, 77-81.

Li, X., Sun, B., Guo, C., Du, W., & Li, Y. (2020). Speed optimization of a container ship on a given route considering voluntary speed loss and emissions. *Applied Ocean Research, 94.*

Lindstad, H., Jullumstrø, E., & Sandaas, I. (2013). Reductions in cost and greenhouse gas emissions with new bulk ship designs enabled by the Panama Canal expansion. *Energy Policy*, *59*, 341–349.

Marquetto, L., Kaspari, S., & Simões, J. C. (2020). Refractory black carbon (rBC) bariabilioty in a 47-year West Antarctic snow and firn core. *Cryosphere 14*, 1537–1554.

Meredith, M. P. (2019). The global importance of the Southern Ocean, and the key role of its freshwater cycle. *Ocean Challenge*, *23* (2), 27-32.

Molders, N., Gende, S., & Pirhalla, M. (2013). Assessment of cruise–ship activity influences on emissions, air quality, and visibility in Glacier Bay National Park. *Atmospheric Pollution Research*, *4*, 435–445.

Muralikrishna, I.V., Manickam, V. (2017). *Chapter Fourteen - Air Pollution Control Technologies*, Environmental Management, Butterworth-Heinemann, 337-397.

NASA (2020). *Milankovitch (Orbital) Cycles and Their Role in Earth's Climate.* Retrieved December, 16, 2021 from: https://climate.nasa.gov/news/2948/milankovitch-orbital-cycles-and-their-role-in-earths-climate/

National Academy of Sciences (2020). *Climate Change: Evidence and Causes: Update 2020*. Washington, DC: The National Academies Press.

NOAA (2007). *The Global Conveyor Belt.* Retrieved January, 11, 2022 from: https://oceanservice.noaa.gov/education/tutorial_currents/05conveyor2.html

NOAA (2015). *What's the difference between global warming and climate change?* Retrieved December, 15, 2021 from: https://www.climate.gov/news-features/climate-qa/whats-difference-between-global-warming-and-climate-change

Papaefthimiou, S., Maragkogianni, A., & Andriosopoulos, K. (2016). Evaluation of cruise ships emissions in the Mediterranean basin: the case of Greek ports. *International Journal of Sustainable Transportation, 10* (10), 985–994.

Pertierra, L. R., Hughes, K. A., Vega, G. C., & Olalla-Tárraga, M. A. (2017). High resolution spatial mapping of human footprint across Antarctica and its implications for the strategic conservation of avifauna. *PLoS One*, *12* (1), e0168280.

Peter H. U., Buesser C., Mustafa O. & Pfeiffer S. (2008). *Risk assessment for the Fildes Peninsula and Ardley Island, and development of management plans for their designation as Specially Protected or Specially Managed Areas*. Dessau: German Federal Environment Agency.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., ….. Stieyenard, M. (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature Journal*, *399*, 429 – 436.

Pino-Cortés E., Díaz-Robles L. A., Cubillos F., Cereceda-Balic F., Santander R., Fu J. S., Carrasco S., & Acosta J. (2021). The black carbon dispersion in the Southern Hemisphere and its transport and fate to Antarctica, an Anthropocene evidence for climate change policies, *Science of The Total Environment*, *778*, 146-242.

Protocol On Environmental Protection To The Antarctic Treaty (1991). Madrid, Retrieved December, 15, 2021 from: https://documents.ats.aq/recatt/Att006_e.pdf

Richter A., Eyring V., Burrows J. P., Bovensmann H., Lauer A., Sierk B., & Crutzen P. J. (2004). Satellite measurements of NO_2 from international shipping emissions. *Geophysical Research Letters, 31* (23).

Rindlisbacher T., & Chabbey L. (2015) Guidance on the determination of helicopter emissions. *Federal office of civil aviation (FOCA)*. Edition 2, reference: COO.2207.111.2.2015750.

Robock, A. (1991). The Volcanic Contribution to Climate Change of the Past 100 Years. *Developments in Atmospheric Science, 19*, 429 – 443.

Salawitch R. J., Fahey D. W., Hegglin M. I., McBride L. A., Tribett W. R., & Doherty S. J. (2019) Twenty questions and answers about the ozone layer: 2018 update. *Journal of Chemical Information and Modeling.*

Souchez, R., Jean-Baptiste, P., Petit, J. R., Lipenkov, V. Ya., & Jouzel, J. (2003). What is the deepest part of the Vostok ice core telling us?. *Earth-Science Reviews*, *60*, 131-146.

South Pole Carbon Asset Management Ltd. (2018). *Greenhouse Gas (GHG) Accounting Report.*

Sun, X., Yan, X. P., Wu, B., & Song, X. (2013). Analysis of the operational energy efficiency for inland river ships. *Transportation Research Part D: Transport and Environment*, *22*, 34–39.

Tichavska, M., & Tovar, B. (2015). Port-city exhaust emission model: an application to cruise and ferry operations in Las Palmas port. *Transportation Research Part A: Policy and Practice, 78*, 347–360.

Tin, T., Fleming, Z. L., Hughes, K. A., Ainley, D. G., Convey, P., ….. & Snape, I., (2009). Impacts of local human activities on the Antarctic environment. *Antarctic Science, 21*, 3–33.

Traut M., Larkin A., Anderson K., McGlade C., Sharmina M., & Smith T. (2018). CO_2 abatement goals for international shipping. *Climate Poicy*, 1-10.

Turner, J., Barrand, N. E., Bracegirdle, T. J., Convey, P., Hodgson, D. A., ….. & Klepikov, A. (2014). Antarctic climate change and the environment: an update. *Polar Record*, *50*, 237–259.

Tzannatos, E. (2010). Ship emissions and their externalities for the port of Piraeus-Greece. *Atmospheric Environment*, *44*, 400–407.

Tzannatos, E., Papadimitriou, S., & Koliousis, I. (2015). A techno-economic analysis of oil vs. natural gas operation for greek island ferries. *International Journal of Sustainable Transportation, 9* (4), 272–281.

Wan, Z., Ji, S., Liu, Y., Zhang, Q., Chen, J., & Wang, Q. (2020). Shipping emission inventories in China's Bohai Bay, Yangtze River Delta, and Pearl River Delta in 2018. *Marine Pollution Bulletin, 151.*

Wartsila (2020). *Wartsila 6L20 Product Guide*. Retrieved December, 25, 2021 from: https://www.manualslib.com/manual/1177300/W-Rtsil-W-Rtsil-20.html?page=20#manual

Weller, R., Minikin, A., Petzold, A., Wagenbach, D., & König-Langlo, G. (2013) Characterization of long-term and seasonal variations of black carbon (BC) concentrations at Neumayer, Antarctica. *Atmospheric Chemistry and Physics*, *13*, 1579–1590.

WMO (2019). Scientific Assessment of Ozone Depletion: 2014 Global Ozone Research and Monitoring Project—Report No. 55, *World Meteorological Organization Global Ozone Research and Monitoring Project*.

Yamaha (2014). *Periodic Maintenance; Replacement Parts; Maintenance Interval Guidelines- Yamaha LF115 Owner's Manual*. Retrieved January, 15, 2022 from: https://www.manualslib.com/manual/1161791/Yamaha-Lf115.html?page=86&term=rpm&selected=2#manual

Yang M. H. (2016). Optimizations of the waste heat recovery system for a large marine diesel engine based on transcritical Rankine cycle. *Energy*, *113*, 1109-1124.

Yau, P. S., Lee, S. C., Corbett, J. J., Wang, C. F., Cheng, Y., & Ho, K. F. (2012). Estimation of exhaust emission from ocean-going vessels in Hong Kong. *Science of the Total Environment*, *431*, 299–306.

Zis, T., North, R. J., Angeloudis, P., Ochieng, W. Y., & Bell, M. G. H. (2014). Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Maritime Economics and Logistics*, *16* (4), 371–398.

Url-1. **<***https://www.global-climate-change.org.uk/5-3-1.php***>.** Access date: 12.01.2022.

Url-2. <*https://en.wikipedia.org/wiki/Lake_Vostok*>. Access date: 11.01.2022.

Url-3. <*https://www.nodc.noaa.gov/archive/arc0001/9900162/2.2/data/0-data/jgofscd/htdocs/achievements/pmn4.html#TECHNICAL*>. Access date: 25.12.2021.

Url-4. <*https://add.scar.org/*>. Access date: 27.12.2021.

Url-5. <*https://www.boat-fuel-economy.com/yamaha-outboard-fuel-consumption-liters*>. Access date: 15.01.2022.

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