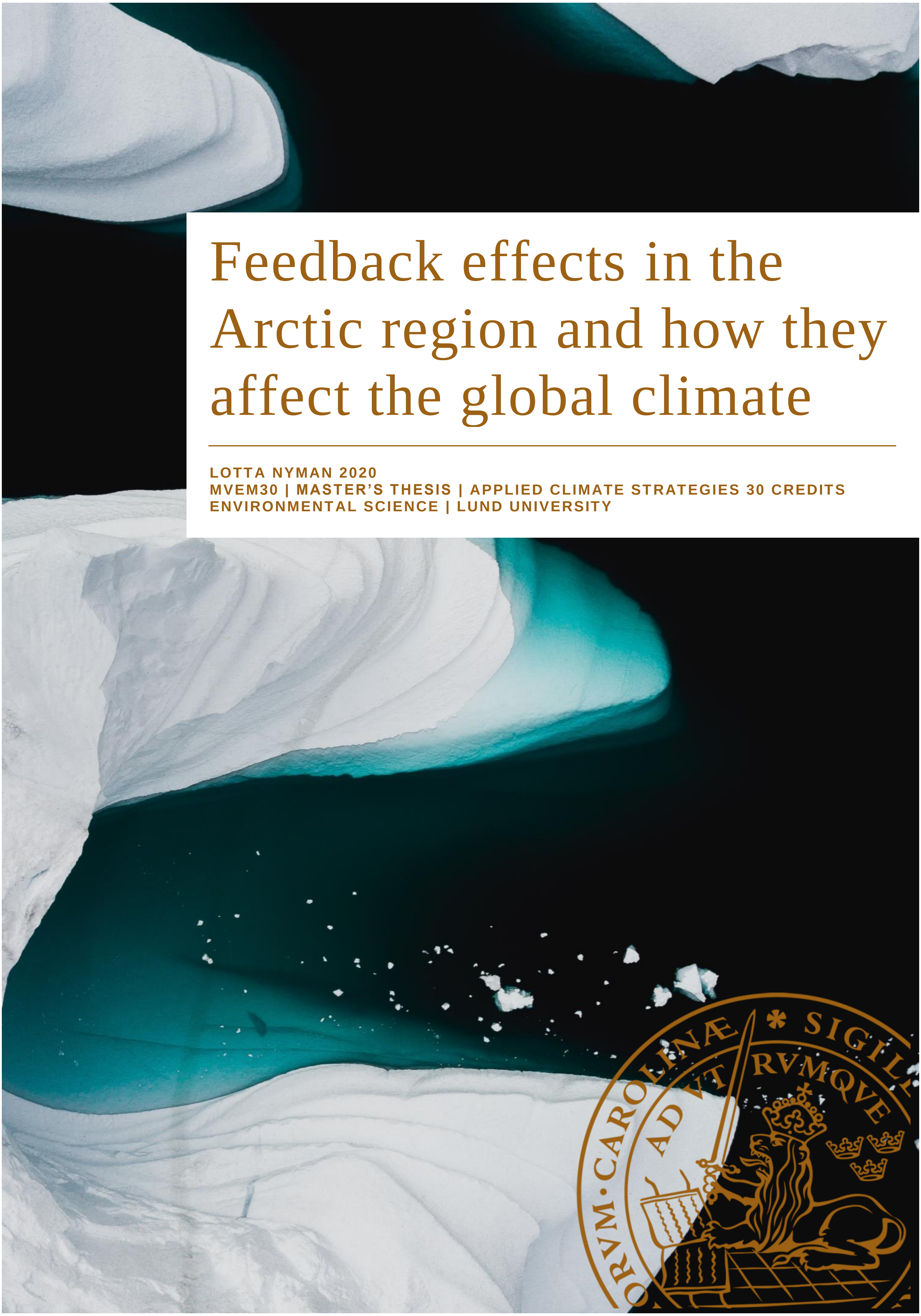

Feedback effects in the Arctic region and how they affect the global climate

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Feedback effects in the Arctic region and how they affect the global climate

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Abstract

The Arctic is warming at a rate two to three times that of the global average. Although only covering a small area of the globe, it is a vital component of the climate system. Through climatic feedback effects the warming is enhanced, and risks leading to further climate change. Simulations of future Arctic change indicate that the region will warm 3-4°C above end of 20th century levels by 2050. Changes of vital components of the Arctic, such as permafrost degradation and decrease of sea-ice and snow cover will enhance the warming, creating a positive feedback to climate. However, the permafrost feedback has yet to be included into these simulations and risk further enhancing the temperature. Thus, the Arctic region is expected to warm at twice the rate projected increase for the Northern Hemisphere alone.

In this thesis, the latest 5 years (2015-2020) of research is analyzed with the aim of demonstrating the speed and extent of Arctic change since the publication of the 2017 SWIPA report conducted by the Arctic Monitoring and Assessment Programme. In addition to focusing on the physical aspects of enhanced warming, the view of Arctic communities and Arctic policy is included to give a comprehensive insight into the components and impacts of Arctic change.

The results indicate that Arctic change is occurring at a faster pace than anticipated by model simulations. The future Arctic is expected to experience further temperature rise, increased precipitation, a retreat of the tundra, and a continuous decrease of sea-ice and permafrost. It is likely that effects on lower latitude weather will increase in frequency, shown through an increased number of wildfires, floods, extensive droughts and extreme temperatures.

Keywords: *Arctic warming, Arctic change, Climate feedback effect, Lower latitude weather, Arctic amplification*

List of Abbreviations

AA	Arctic Amplification
AMAP	Arctic Monitoring and Assessment Programme
AMOC	Atlantic Meridional Overturning Circulation
AR5	IPCC Fifth Assessment Report
C	Carbon
CH4	Methane
CMIP5	Coupled Model Intercomparison Project phase 5
CO2	Carbon Dioxide
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
PCF	Permafrost Carbon Feedback
PI	Pre-industrial
RCP	Representative Concentration Pathway
SAT	Surface Air Temperature
SSPs	Shared Socioeconomic Pathways
SWIPA	Snow, Water, Ice and Permafrost in the Arctic

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Introduction

The Arctic region is warming up to two to three times as fast as the global mean (Serreze and Barry, 2011; Zhang, et al., 2019; AMAP, 2017), a feature named Arctic amplification (IPCC, 2014b). The rise in greenhouse gas concentrations in the atmosphere has increased the global temperature and has had staggering effects on the Arctic, which is especially sensitive to temperature (AMAP, 2017), and has recently experienced a warming unprecedented in the past 2000 years (Walsh, 2014). Environmental changes in response to changing climatic conditions and amplified warming risk further enhancing the global warming through various climatic feedbacks (Yumashev, et al., 2019). The Arctic is now experiencing a fundamental shift where cryospheric components are being altered with consequences for Arctic communities, species, ecosystems and global weather (AMAP, 2017).

The warming has resulted in, and is a result of, an observed decline of Arctic sea-ice (Notz and Stroeve, 2016), and snow cover. Reductions are associated with a decrease of surface albedo (Zhang, et al., 2019) which will lead to greater absorption of solar radiation, in both ocean and on land, enhancing warming further and leading to more sea-ice and snow cover decline (Thackeray and Hall, 2019). Frozen permafrost soil is starting to thaw, often for the first time in thousands of years, releasing greenhouse gases to the atmosphere (Turetsky, et al., 2019). A retreat of the Arctic tundra is changing ecosystems and vegetation dynamics, allowing for a shrubification of the biome (IPCC, 2019) and advancing tree lines, and the Greenland ice sheet is at risk of irreversible changes with sea-level rise as a result (IPCC, 2018). Model simulations of future changes indicate that the temperature rise in the Arctic will be 3-4°C above the end of the 20th century temperature by 2050 (AMAP,2017), for medium to high emission scenarios. This would suggest that some of the changes in the Arctic would continue even if greenhouse gas concentrations in the atmosphere are reduced (AMAP, 2017).

The ratification of the United Nations Paris Agreement meant introducing the aim of keeping the global mean temperature rise to below 1.5°C to 2°C compared to pre-industrial levels (IPCC, 2018), a goal which should be implemented in Arctic policy, and that has the potential to limit further damage to the cryosphere (Hjort, et al., 2018).

It has been hypothesized, and staggering evidence now shows that Arctic change has the potential to influence the global climate, for example through changes in lower latitude weather. More frequent extreme weather has been observed and linked to both Arctic change and Arctic amplification (Cohen, et al., 2014).

This thesis explores recent updates to trends and projections examining these climate feedback effects in the Arctic region, and their effect on the global climate. The Arctic Monitoring and Assessment Programme (AMAP, amap.no) which is a scientific Working Group under the Arctic Council, produced the report “Snow, Water, Ice and Permafrost in the Arctic” (SWIPA), conducted between 2010 to 2016, and published in 2017 based primarily on peer-reviewed observations, methods, and studies. The findings of the report show the current environmental state of the Arctic, and changes in the climate that had occurred up until its publication. Here I will conduct a comprehensive update of the new research in the field since that publication. Using literature reflecting the last 5 years of research (2015-2020), the thesis aims to identify the changes and development of climate feedback effects as a result of enhanced global warming, how this affects policy implementation and Arctic communities, and aims to identify implications for the global climate. I suggest that with climate change and amplified warming happening faster in the Arctic than anywhere on the globe, the field is swiftly changing and reaching new conclusions, and should therefore have seen extensive new research under the course of a half decade.

Research questions and aim

The intention of the thesis is to, through a literature review, identify, update and summarize the new and current research on Arctic climate change, key feedback processes, and changes in the cryosphere, and to identify the projections for the future global climate. Previous research will be reviewed and the current state of the Arctic environment will be presented. The main research questions will be:

- How has the research on Arctic feedback effects changed since the publication of SWIPA 2017?
- How will arctic warming affect the global climate in terms of greenhouse gases, sea level rise, vegetation dynamics and effects on lower latitude weather?
- What will the 1.5 and 2°C targets mean for the Arctic in terms of Arctic amplification, feedbacks and policy?

The focus will be on the feedbacks that still hold a lot of uncertainties and are often not included in the climate models. Hence, their impact on climate change has remained uncertain, and subject to scientific debate.

Ethical reflection

The climate feedback effects of interest in this thesis have implications foremost for the inhabitants of the Arctic region. On that note it can be a sensitive subject, depending on the results of the thesis. As the Arctic region is getting increasingly wetter and warmer, it is clear that these transformations will have implications for people and resources, as well as ecosystems, both locally and on a global scale (AMAP, 2017). Social, economic and political factors are also changing with the changing climate: notably recreation and tourism, as well as local development, migration and shipping in an ice-free Arctic (AMAP, 2017).

As such, the findings presented in this thesis may show that changes in Northern Hemisphere weather and sea-level rise associated with the changes in the Arctic will affect the Arctic species as well as the livelihoods of its inhabitants. This is especially important since some of the changes appear irreversible (AMAP, 2017).

The amplified warming is projected to affect species and their distribution, including species composition, production, and ecosystem structure and functions (IPCC, 2019). Limiting the warming to 1.5°C is of great importance for the Arctic, thus putting pressure on global efforts to reduce greenhouse gas emissions, and to further help local Arctic communities with adaptation.

Delimitations

The thesis will be a qualitative literature review. Since the publication of SWIPA in 2017, new research has emerged in the field. Therefore, the literature review is limited to literature published between 2015 and 2020. This narrows down the amount of research available and will make the subject easier to grasp, whilst including research not published in SWIPA 2017. The thesis will focus on the Arctic feedback effects in general and the overall implications they have for the global climate. Each of the feedbacks will only be discussed in a limited capacity to paint a bigger picture of how they function in relation to each other and the global climate system.

The thesis is limited to the feedback effects: sea-ice and snow cover, sea-level rise, vegetation dynamics, and permafrost. These feedback effects still hold uncertainties in their future changes and future contribution to climate change and are poorly represented or excluded in climate models, thus being of interest. As potential big contributors to Arctic change they are subject to scientific debate with a likely expansion of research in the area in the timespan included in the thesis. Further, they are considered in SWIPA 2017 and can thus generate a comparison with recent research. Due to the timeframe of the thesis, the number of feedback effects analyzed were limited. The more established feedback effects that are largely understood (and mostly included in climate models) are, if mentioned, only so to create context and will not be discussed thoroughly. This includes the sea-ice albedo feedback in relation to sea-ice loss, the water vapour feedback, cloud feedback, lapse-rate feedback and Planck feedback, to mention a few (Pithan and Mauritsen, 2014). Already being included in models and deemed to be a part of the Arctic amplification they are thus not discussed in this thesis, although their part in Arctic warming is acknowledged.

The thesis will focus on the physical changes occurring in the Arctic and the cryosphere and the future implications that brings, as well as how they affect the global climate. Both Arctic communities and Arctic policy will be included to give a better understanding of Arctic change, but effects on human populations, communities and policy implications will not be discussed on a global scale. Ecosystem services are not the focus of the study but may be mentioned in relation to changes in the global climate system.

Henceforth, the thesis will be limited to the 1.5°C and 2°C targets in accordance with the Paris Agreement (FCCC/CP/2015/L.9/Rev.1). There are several future emissions scenarios or Representative Concentration Pathways leading to greater temperature increases (IPCC, 2018), which will be mentioned in relation to contemporary and projected feedback effects.

Structure of the thesis

The thesis disposition can be seen as a whole in Figure 1. Each chapter is comprehensively described through the introduction with aim and research questions, description of the method, introduction to the literature review, and in the final stage the discussion, conclusion and recommendations for future work.

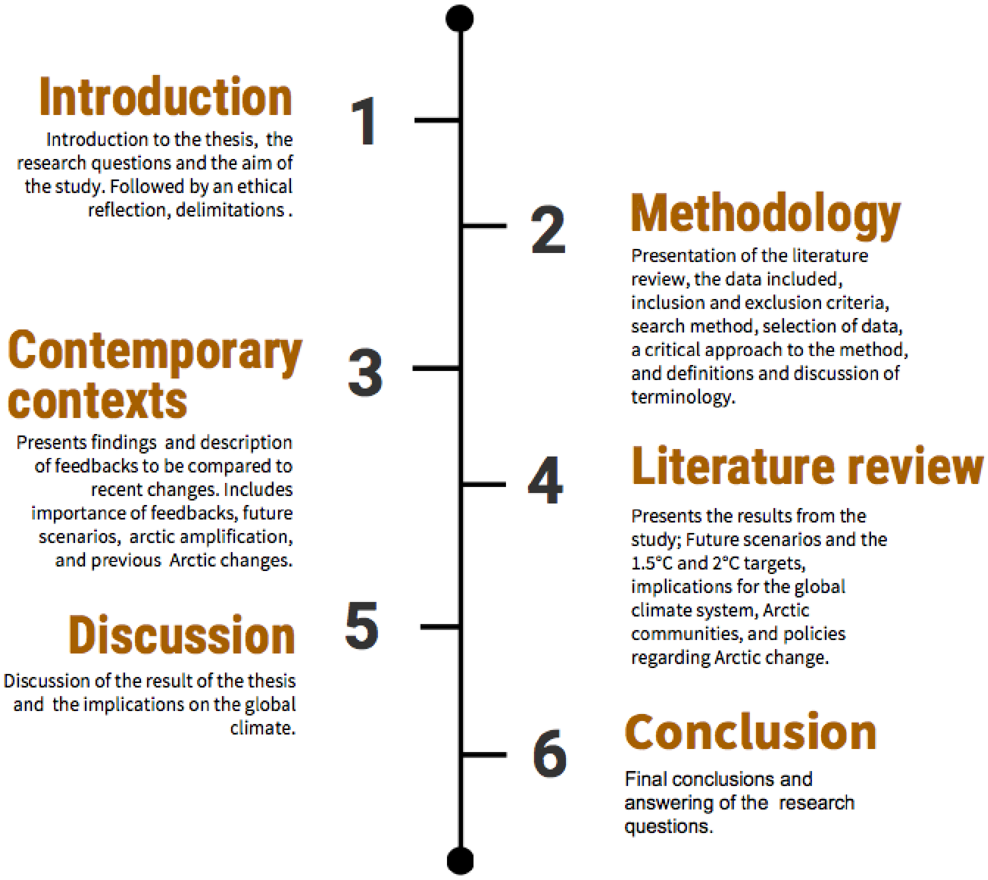

Figure 1. Schematic picture displaying the thesis structure. Illustration: the author’s own.

Methodology

The thesis will be a qualitative literature review describing relevant research in the field, which will provide an overview of the current state of the environment and aims to provide supporting evidence by underlining the significance of the research (Ridley, 2012).

Literature review

A literature review can serve different purposes and can be divided into two different parts: both the process of conducting it and the product of the review. The process of creating the review refers to the search process, how it is conducted, the influence on the research questions and the identification of theories and previous research (Ridley, 2012). The literature identified during the review will be paramount in the analysis of the data. The second part is the product where the literature review can be used to identify the gaps in the research and thus to identify the research problem (Ridley, 2012; Booth, et al., 2016). It is an opportunity to draw connections and situate the review amongst other research (Ridley, 2012; Hart, 2009). The purpose is to provide an overview of both the knowledge and the questions on the topic to be researched (Bell, 2010).

A literature search increases the awareness of the subject and will put the writer in a better position to make informed choices and avoid duplication of existing research (Ridley, 2012; Hart, 2009). It is furthermore a way to evaluate the relevance of one's own work and to provide a framework for key concepts and structuring of the thesis (Hart, 2009). Building up a knowledge of the research available in the field is essential to analyzing the work critically and can be a justification for a new approach in a well-researched subject (Hart, 2009). The credibility of the findings can be enhanced by demonstrating how thorough the search has been and reviewing it in the search method (Booth, et al., 2016).

In a qualitative literature review you analyze the text thoroughly and identify the essential parts (Esaiasson, et al., 2017). The review will take a *dedicated* approach, meaning that the literature review will appear in the thesis in the form of an individual chapter (Ridley, 2012). Further, the literature search will have a semi-systematic approach, meaning that the literature will be searched systematically to increase validity and avoid selection bias (Booth, et al., 2016). Selection bias is when the reviewer selects studies based on whether they are interesting or support a prior belief, rather than by relevance (Booth, et al., 2016). The semi-systematic approach the thesis adopt will increase the literature review's reliability and the methodological strategies will be reproducible.

As an addition to the systematic approach, the research field can be extended through the snowball technique. It entails following up references from the bibliographies in the research of the review, and is a way of following up on previous research (Ridley, 2012). It can be used as a way of finding new or redefined key words in the search process, or a natural way of going forward as authors are continuously being recognized in the subject.

Data

The information used in this review will exclusively be material that has been the subject of peer-review. It is important to constantly evaluate the sources used in academic writing and make sure that these are traceable (Ridley, 2012). Only academic texts will be considered although I were not restricted to one type of publication. As a literature review, the literature itself will be the main source of data and the focus of the thesis (Ridley, 2012).

The bibliographical database Web of Science (webofknowledge.com) will be used as information source in this thesis. A further search has been conducted on the multidisciplinary scientific journal Nature's research site (nature.com). The journal publishes weekly peer-reviewed research. This will ensure I acquire the latest research as journals contains the most recent ideas in a discipline (Ridley, 2012).

Since the subject of our literature review, Arctic feedback effects, contains many uncertainties and assumptions regarding future projections it can be assumed that there will be gaps in the research material available.

Criteria for inclusion and exclusion of studies

In this section, it will be recorded how the decisions of which studies to include and which to exclude were made.

Studies to be included in the literature search: can not have been published before 2015 and hence have not been included in the 2017 SWIPA report; have to be peer-reviewed, and; have to be published in English. Literature describing well-established feedbacks can have been published before 2015. The type of articles that are included in the study are for the database Web of Science;

articles, proceedings papers, reviews, early access articles. For the journal Nature, the included articles are: research and reviews.

Studies that are excluded include articles that are not related to the aim of the study (Friberg, 2017), not peer-reviewed or overview studies that do not include their own results. During the literature search, the types of articles excluded are for Web of Science: meeting abstracts, book reviews, data papers, news items; and for Nature: comments and opinion, correspondence, news, news and views and special features.

Search method

A preliminary scoping search was conducted to get an overview of the research available on the subject. It was conducted on Web of Science. At this point in the research the focus was on established feedback effects that are well researched and have large implications for Arctic amplification, as a means of getting a large amount of material. A scoping search focuses on identifying existing material and gives an indication, ahead of the main search, of the existing quantities of previous research (Booth, et al., 2016).

The search words included: *Arctic feedback effect*, *sea-ice albedo*, *permafrost feedback loops* and, *global climate*. Boolean logic operators and truncation were used to get specific search results and to indicate what to be included and excluded (Ridley, 2012; Booth, et al., 2016). The alternative combinations used in the initial search are shown in Table 1.

The search generated 25 articles. The titles were browsed to identify articles related to the subject, and once identified, the abstracts were read to select current studies and search words to be used in the main search. After reading the abstracts, 8 articles were selected to be of relevance. These were read and the articles analyzed shown in Table 1 (search 1).

Table 1.
Search 1, Preliminary scoping search using different keyword combinations and Boolean logic.

	Block 1	**Block 2**	**Block 3**	**Block 4**
Concept/term	Arctic feedback effect	Sea-ice albedo	Permafrost feedback loop	Global climate
Alternatives	"Arctic feedback*" "Arctic feedback effect*" "Arctic feedback loop*" "Arctic feedback mechanism*"	"Sea-ice albedo*" "Sea-albedo*" "Albedo feedback*"	"Permafrost feedback*" "Permafrost feedback loops*" "Permafrost feedback effects*" "Permafrost decrease*"	"Global climate
Relationship	Arctic feedback* OR Arctic feedback effect* OR Arctic feedback loop* OR Arctic feedback mechanism*	Sea-ice albedo* OR Sea-albedo* OR Albedo feedback*	Permafrost feedback* OR Permafrost feedback loops OR Permafrost feedback effects* OR Permafrost decrease*	Global climate* AND (Change* OR Warming*)

Following the preliminary scoping search the main search was conducted on Web of Science and the journal Nature. The keywords were further modified to achieve desired results. For the bibliographical database and the journal the keywords remained the same to keep a systematic approach to the literature search, and generate a cohesive result. The search words included: *Arctic*, *feedback*, *global climate*, *permafrost*, *Arctic communities*, *Arctic policy*. The keywords were distinctly narrowed down in an effort to achieve a bigger result. The generated articles were then analyzed and selected in accordance with the previous method. Results can be observed in Table 2 for the search in the journal Nature and in Table 3 for the search in the database Web of Science.

Table 2.
Search result for the journal Nature.

DataBase: Nature	**Searchword**	**Inclusion/exclusion criteria**	**Hits**	**Selection 1**	**Selection 2**
#1	Arctic AND Feedback AND “Global climate” AND Permafrost	Dates: 2015-2020	52		
#2	Arctic AND Feedback AND “Global climate” AND Permafrost	Dates: 2015-2020 Article type: Research and reviews	48	20	12
#3	Arctic AND Feedback AND “Global climate” AND Permafrost OR “Arctic communities” OR “Arctic policy”	Dates: 2015-2020 Article type: Research and reviews	64	24 (6)	14 (4)

Table 3.
Search result for the bibliographical database Web of Science.

DataBase: Web of Science	**Searchword**	**Inclusion/exclusion criteria**	**Hits**	**Selection 1**	**Selection 2**
#1	Arctic* AND feedback* AND "global climate"* AND permafrost* OR "Arctic communities"* OR "Arctic policy"*	Dates: Last 5 years	144	20 (15)	12 (9)

Selection I

In the first selection, the titles and abstracts were read in combination. From the search result generating 48, 64 and 144 hits the articles were chosen which followed both the aim of the thesis and the criteria for inclusion. Some of the articles were identified several times in different searches and are therefore only counted once. This can be assumed to indicate that the search words are well developed and that a big part of the field is covered, as articles reoccur in several searches. The number between the parentheses in Tables 2 and 3 is the number of 'unique' articles, as some of the articles were found in the search on both Web of Science and Nature. The final number of unique articles from selection I was 41.

Selection II

In selection II the 41 articles selected from selection I were all read fully. Some of the articles did not match the aim of the thesis or the criteria for inclusion and were thus excluded. Some of the abstracts previously read fit into the search criteria of the thesis but was later discovered to have a different aim and was thus excluded. The total number of articles that were chosen after being read was 25 and are compiled in Appendix I.

Critical approach to the method

Since the literature review has a semi-systematic approach, this reduces the risk for selection bias (Booth, et al., 2016). However, a large part of the literature included in the review was not found during the initial search, but was instead gained through the snowball technique during the course of the thesis. This implies that some selection bias could be involved in the inclusion of articles, or a limited set of search terms, and/or a too strict Boolean criterion, therefore limit the ability for methodological reproduction of the results presented in the thesis. Although selection bias risks being a part, the articles were chosen as a way of referring to the primary research and thus included several more articles than were found in the initial search.

Definitions and discussion of terminology

Description of the cryosphere

Collectively, the geographical areas characterized by the frozen state of water are called the cryosphere (AMAP, 2017) and in this thesis it refers to the polar regions in the Northern Hemisphere such as glacial ice, the sea-ice, the boreal biome and both the continuous and discontinuous permafrost zone that show the characteristic cryosphere elements; persistent snow cover during the winter season, permafrost, ice caps, sea-ice and glaciers (AMAP, 2017; IPCC, 2019).

The importance of the cryosphere

As the global mean temperature changes, so does the cryosphere in the Arctic region. The change in the amount of frozen water ultimately results in a change in both the gaseous and liquid forms, making the cryosphere closely linked to the Arctic hydrosphere (AMAP, 2017), something that will have global implications.

The cryosphere is a key component of the global climate system in regulating the global heat transfer (AMAP, 2017; IPCC 2019) and is connected to the rest of the Earth system through both the ocean and atmosphere. Global, regional and local climate is affected by the cryosphere as the Arctic region receives and cool down heat from lower latitudes (AMAP, 2017). Further cooling is achieved through the cover of ice and snow that reflects shortwave radiation from the sun back to space, also called the albedo-effect (AMAP, 2017).

Cryospheric influence on the amount of CO_2 present in the atmosphere follows as considerable volumes of carbon (C) are stored as organic matter in Arctic soils, which hold twice the amount of C as the atmosphere does (Turetsky, et al., 2019; UNEP, 2012).

There are many different factors in play when it comes to Arctic terrestrial snow cover. However, though this thesis will focus on and primarily mention snow cover extent, it will not further discuss characteristics such as snow depth, snow water equivalent, or snow properties, although they are acknowledged as an important part of the cryosphere with effects on the Arctic and global climate system.

Definitions

Under the course of the thesis, the terms resilience and risk will be used, in both the context of human and ecological systems. With resilience in the context of Arctic climate change, the thesis implies the capacity (of communities and ecosystems) to manage climate related stresses and shocks (IPCC, 2014b). Risk indicates the impacts on the climate, as a result of the vulnerability and adaptability of human-, ecological-, and climatic systems when in interaction with climate hazards (IPCC, 2014b). Climate hazards includes both events and trends.

Contemporary context

The aim of this chapter is to present current literature on Arctic change and feedback effects, to present the state of the environment to later be compared to the findings of the literature review which will describe the current state of the environment, future projections, effects on Arctic communities and policy implications. The chapter will allow inclusion of literature published before 2015 to later compare it to more recent research.

The importance of feedbacks

Climate feedback effects are needed to understand and describe global warming, and feedbacks are processes that may amplify or diminish effects of different climate forcings (Goosse, et al., 2018). The term “climate forcing” defines the radiation imbalance at the troposphere in the atmosphere and in the end – depending on the sign - whether the climate system will move towards cooling or warming through alterations in the rate of energy received and emitted (Denning, 2018). The interaction expresses itself as a disturbance in one climate quantity that changes a second quantity, and the second change leads to further changes in the first quantity. A feedback where the disturbance (warming) is increased or amplified is called a “positive feedback” whereas a reduction of the initial warming is a “negative feedback” (IPCC, 2014b, Annex II). The dynamics of the polar climate system are driven by interactions between radiative and non-radiative sources (Goosse, et al., 2018). The starting point of feedbacks can be initiated by both natural and anthropogenic forcings, such as volcanic eruptions or increased greenhouse gas emissions (GHG), respectively (Serreze and Francis, 2006).

Future scenarios

Looking into the future, global scenarios and climate projections are often used from the Fifth IPCC Assessment Report (AR5) referred to as scenarios following the RCPs (Representative Concentration Pathways). Four future scenario emissions projections have been identified, which describe a range of different pathways of GHG emissions, land use and pollutant emissions during the 21th century (IPCC, 2014b, SPM 2.1). Taken into account are the main drivers of anthropogenic emissions, such as land use, technology, economic activity etc. The four pathways include an optimistic mitigation scenario (RCP 2.6), two middle scenarios (RCP 4.5 and RCP 6.0) as well as a business-as-usual scenario containing high emissions (RCP 8.5), with the numbers indicating the radiative forcing (W/m^2) by 2100 (IPCC, 2014b, SPM 2.1).

Projections using climate models indicate that the Arctic region will keep on warming faster than the global mean. For all RCP scenarios, reductions in Arctic sea-ice are projected to be observed during the whole year (IPCC, 2014b, SPM 2.2) at some point in the 21st century. Reductions for RCP 2.6 and RCP 8.5 are shown in Figure 2. The scenarios all have a long timescale, of hundred years, to project what the changes may be by 2100. The extent of near-surface permafrost will be affected by the temperature increase, and decrease to a certain degree for all scenarios. Climate models indicate that changes in climate will be more pronounced in the Arctic region than for lower latitudes. The SWIPA report states that the temperature rise for RCP 4.5 will be 3-5°C and 5-9°C by mid-century and late century respectively, - resulting in an ice-free ocean in the beginning of winter and covered in thin ice by the end of winter for some models (AMAP, 2017).

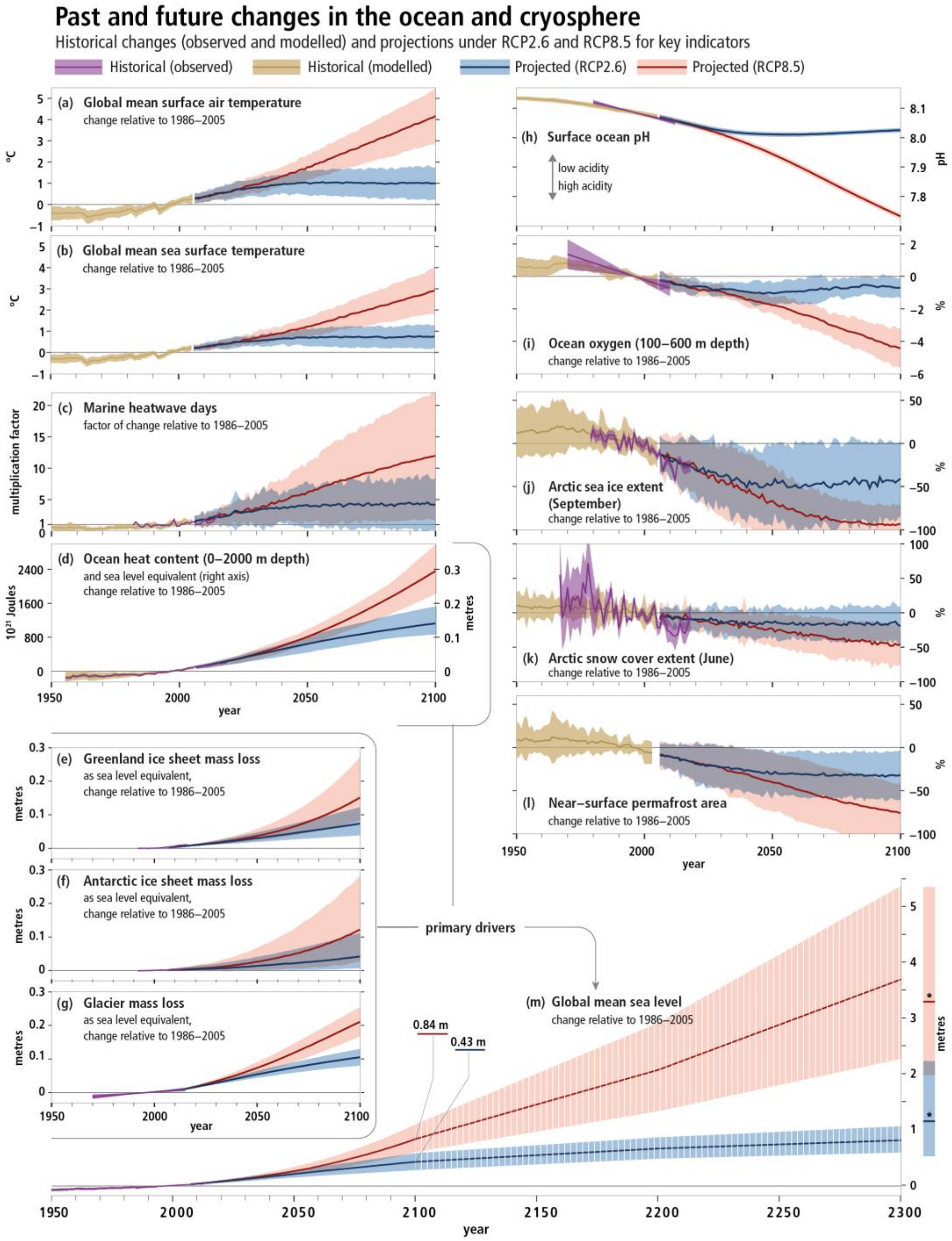

Figure 2. Past and future changes and projections in the ocean and cryosphere under RCP scenarios 2.6 and 8.5. Source: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 2018, Figure SPM1.

Arctic amplification

Warming in the Arctic region is occurring at a faster pace than the rest of the globe as shown in both climate models and observational data (Dai, et al., 2019). The feature, making the region warmer than the global mean, is called Arctic amplification (AA) (IPCC, 2014b). The increased warming has occurred as much as two to three times faster since the 1980s, compared to the global mean (Serreze and Barry, 2011; Zhang, et al., 2019; AMAP, 2017), and the feature can be observed in surface air temperature trends during the last 50 years (Serreze and Barry, 2011), shown in Figure 3. It is considered a characteristic of the climate system and is visible in instrumental records, paleoclimatic records, covering millions of years, and climate model projections (Serreze and Barry, 2011).

The mechanisms causing AA have long been under debate, but recently a better understanding of its mechanism have emerged. It is a phenomenon caused by both local and remote forcings and feedbacks (Stjern, et al., 2019). Many studies indicate that the surface albedo feedback is the main driver of AA. However, AA still occurs in climate models where surface albedo feedback is not included (Dai, et al., 2019; Pithan and Mauritsen, 2014). Further, it does not explain why AA is strongest during the winter season, when the ice-albedo effect is supposed to be its least effective (Dai, et al., 2019; Serreze and Barry, 2011). However, Dai et al. (2019) show that both sea-ice and significant sea-ice loss is needed for a large AA to occur as a result of GHGs. The reduced summer ice cover increases the energy storage in the exposed ocean, which during the winter season is released as redundant long-wave radiation - causing warming during that season (Dai, et al., 2019). Although occurring in each season, AA is strongest during the winter season (Cohen, et al., 2014).

The AA is anticipated to strengthen during coming decades as a result of (and resulting in); a longer sea ice melt-season, higher amount of aerosols and soot covering high albedo areas, changes in circulation (oceanic and atmospheric), and increases in atmospheric water vapor among other factors (Serreze and Barry, 2011), possibly affecting both mid-latitude weather and climate outside the Arctic region (Dai, et al., 2019).

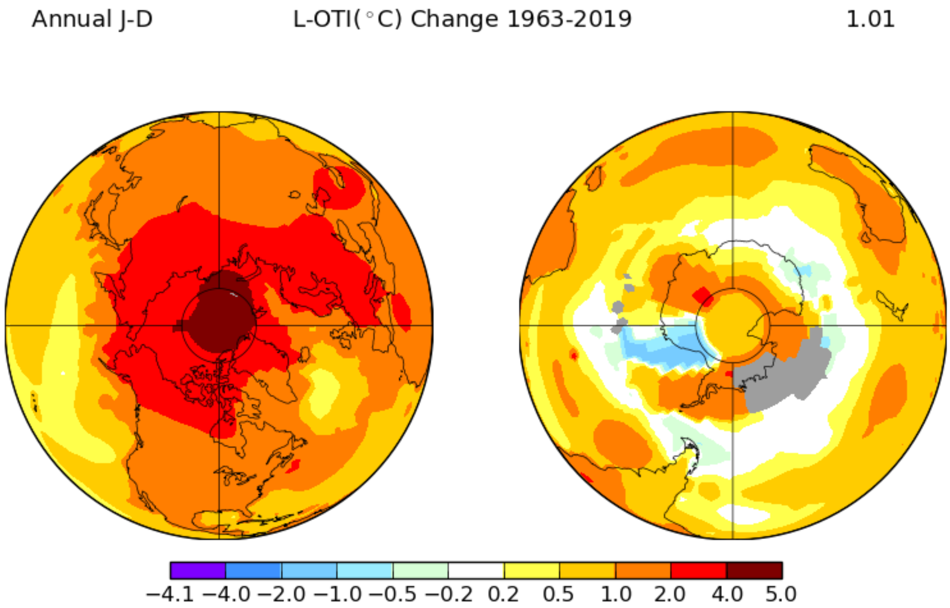

Figure 3. Change in annual surface air temperature in °C over the period 1963-2019. The left globe displays the changes in the Northern Hemisphere and the Arctic region, the right globe Antarctica. Source: NASA Goddard Institute for Space Studies, (https://data.giss.nasa.gov/gistemp/maps/)

Climate change in the Arctic region

Sea-ice and snow cover

Temperature rises are expected, foremost the surface air temperature (SAT), as a response to an increase in greenhouse gas emissions. This is projected to be amplified over the Arctic region compared to the northern hemisphere in general, leading to retreat and thinning of sea-ice and snow cover (Serreze and Francis, 2006). One of the important climatic processes that are part of this is the ice-albedo feedback. Albedo is the measure of the Earth’s reflectivity, which is very high for snow and ice. As the Earth warms it results in a reduction in the sea-ice and snow cover extent. Less extent means that areas with lower albedo are exposed, creating higher solar absorption at the surface which leads to additional warming and a greater reduction of the snow and ice cover (Goosse, et al., 2018; Serreze and Francis, 2006; Zhang, et al., 2019; Thackeray and Hall, 2019). In that sense, it is a positive feedback as the original warming (e.g. from increased GHG concentrations) is amplified.

Permafrost

Permafrost is ground that is frozen at or below 0°C during the whole year for at least two consecutive years (UNEP, 2012). Areas with permafrost are subdivided into three different zones; the continuous permafrost zone (>90% frozen ground), the discontinuous zone (>50%) and the sporadic zone (<50%) (Froese, et al., 2008; UNEP, 2012). The surface layer of the permafrost is the active layer which thaws in the summer to again freeze in the winter. Permafrost keeps both animal remains and plants from decay, storing the organic matter (UNEP, 2012). Discontinuing the decomposition from occurring, the soil will still hold the organic matter, creating a carbon sink (AMAP, 2017).

The dominant factor regulating the distribution of permafrost is air temperature. With half of the organic matter in the permafrost located in the top 3 m of the soil (UNEP, 2012), it is vulnerable to rising SAT. When the permafrost thaws, the organic matter locked in the soil will start to decay again and will start to release both CO_2 and methane (CH_4) (both GHGs), thus magnifying the warming (UNEP, 2012). It is important to understand that the gases are not locked in the soil itself, but it is the microbial activity that will resume and ultimately convert the organic matter to CO_2 and CH_4 in the process. Once converted and released to the atmosphere, the warming will increase and create further permafrost degradation – the permafrost carbon feedback (PCF).

An increase in permafrost temperature has been noted since mid- 1980s and has continued until 2015 and the publication of the SWIPA 2017 report. The highest temperature increase was located within the continuous permafrost zone where the rise amounted to 1.4-1°C per decade (AMAP, 2017).

During the 21st century, some fraction of the permafrost will be thawed, releasing CO_2 and CH_4. The thawing may continue for decades (Schuur, et al., 2015), as shown in Figure 2, even after the anthropogenic GHG emissions have ended, and is considered irreversible on a human timescale (UNEP, 2012).

Lower-latitude weather

As a result of Arctic amplification there is a decrease in the near-surface north-south temperature gradient (Screen and Simmonds, 2013). However, this is not caused by loss of sea-ice alone but driven by a number of different processes associated with AA (Screen and Simmonds, 2013). The warming of the Arctic region expresses itself as changes in the components of the Arctic system, such as sea-ice and permafrost, but the changes are expected to affect both lower latitudes and the global climate (Walsh, 2014).

As the Arctic is warming and the sea-ice diminishing, extreme weather events have been reported in the mid-latitudes of the Northern hemisphere

(Cohen, et al., 2014), notably anomalously cold winters (Tang, et al., 2013). Although there is a general trend toward warmer winters since the 1960s, the number of days in a row below freezing has increased, and there has been a decrease in the minimum temperature. This change has been attributed to the AA in the Northern Hemisphere (Cohen, et al., 2014). Between the years 2007 and 2013 the lowest sea-ice extent was observed in the Arctic (Cohen, et al., 2014), concurring with several anomaly cold winters in mid-latitudes (Tang, et al., 2013).

Literature review

Future scenarios and the 1.5° and 2°C targets

Out of the scenarios represented by the IPCC (2013), RCP 2.6 is the one that is *likely* to keep the global average temperature increase (relative to its pre-industrial (PI) level) below 2°C in accordance with the United Nations Paris Agreement (FCCC/CP/2015/L.9/Rev.1), but will require extensive mitigation efforts. Another relevant scenario is RCP 4.5 which will result in a >2°C global temperature rise (IPCC, 2018). Simulations following the RCP 4.5 scenario made by global climate models indicate a warming of 2.0 ± 0.3°C for the years 2046-2065 (Overland, et al., 2019). This would mean that the scenario is possible under the Paris Agreement as a +2°C warming falls within the range of uncertainty (IPCC, 2018). Although looking at 2100 this precedes the limit as simulations show a temperature rise of 2.4 ± 0.5°C in 2100 for the same scenario (Overland, et al., 2019).

Since the AR5 in 2014 there has been progress made in understanding the processes and specific characteristics of importance to limit the temperature rise to 1.5°C (IPCC, 2018). Hence new scenarios have been developed to better take into account the socio-economic drivers, new climate policies and the availability and effectiveness of various technologies to remove carbon dioxide (IPCC, 2018). These are called the Shared Socio-Economic Pathways (SSPs).

With the new approach, two new very low socioeconomic pathways and emissions scenarios have been proposed, SSP1 and SSP2, that can reach a radiative forcing level at the end of the century of 1.9W/m$_2$, hereafter called SSP1-1.9 and SSP2-1.9. Simpler Integrated Assessment Models (IAMs) have shown that these pathways are consistent with the 1.5°C target in the aspects of the rate of emissions reduction, peaking time of the emissions, and low-carbon energy deployment rates (IPCC, 2018). Paramount is the time perspective, and whether they will keep the surface temperature below the threshold during the entire 21$_{th}$ century or if the temperature limit will be exceeded, only to later drop below 1.5°C above pre-industrial levels. If it is the latter, this is referred to as an overshoot (IPCC, 2018).

There are differences to be expected when it comes to risk, if the 1.5°C limit is achieved before or after 2100, if it is constant for millennia (Seneviratne, et al., 2018), or if the temperature will exceed and then return to 1.5°C in the case of an overshoot. The delay of effects connected to temperature and radiative forcing makes it important to consider the time aspect, as these elements may affect the climate over a longer time period, and is possible to keep changing even after a stabilization at 1.5°C is achieved (Seneviratne, et al., 2018). Exceeding the 1.5°C goal can start processes and lead to feedbacks that will result in a greater enhance in temperature (IPCC, 2019). Seneviratne et al. (2018) state that all the mitigation pathways available today linked to a warming of less than 1.5°C by 2100 risk overshooting, and there is a 50% risk of the temperature being higher than that during the same time.

No matter which one of the scenarios is followed, the Arctic is still projected to change in ways and at a pace never seen before in the historical records, in terms of temperature, snow cover, permafrost, and changes to the Arctic ecosystems (Overland, et al., 2019). In the case of an overshoot, the risk for reaching tipping points is higher and could lead to permanent loss of ecosystems. Species able to adapt to the rapidly warmer temperatures could instead have problems later to adapt to returning temperatures pre-overshoot (Seneviratne, et al., 2018). It is further important to know that global mean temperature alone might not be good enough as an indicator to imply which changes might occur as systems react to other factors as well, such as the concentrations of CO_2 (Seneviratne, et al., 2018), and that global measures not can represent that of regional ones.

If ambitious sustainable development and mitigation were to be implemented, this would lower the vulnerability and increase the resilience, possibly occurring before 2100. This implies the importance of the time aspect, that is, when in time the temperature stabilization occurs (Seneviratne, et al., 2018).

Overview of the research field

The literature acquired during the literature search and throughout the thesis gives an indication of where research focus is located and which feedback effects that are largely represented in the academic literature. However, more research and literature are available for specific fields. Although the feedbacks covered in this thesis have historically been poorly represented in climate models and thus hold uncertainties, research is expanding. Table 4 display the number of articles found for each feedback effect or section. Arctic communities and policy is included although not being feedback effects since they are putting the thesis in a greater context. Lower latitude weather is further included to indicate the amount of research available. Some articles feature several feedback effects and are thus included in several sections.

Table 4. Articles included in the thesis divided on each subject. Articles published before 2015 which may be referred to prior, as well as IPCC, UNEP and AMAP reports are not included.

Feedback / Section	**Articles**		**Total number**
Sea-ice and snow cover	Notz, et al., 2020 Gerland, et al., 2019 Perovich, et al., 2019 Post, et al., 2019 Richter-Menge, et al., 2019 Zhang, et al., 2019	Thackeray and Hall, 2019 Goosse, et al., 2018 Screen, et al., 2018 Bintanja and Andry, 2017 Notz and Stroeve, 2016 Nilsson, Polvi and Lind, 2015	12
Sea level	Shepherd, et al., 2020 Overland, et al., 2019 Golledge, et al., 2019	Pattyn, et al., 2018 Goelzer, et al., 2017	5
Vegetation dynamics	Liu and Xue, 2020 Brown, et al., 2019 Richter-Menge, et al., 2019 Post, et al., 2019 Stewart, et al., 2018 Wheeler, Høye and Svenning, 2018	Fauchald, et al., 2017 Kaarlejärvi, Eskelinen and Olofsson, 2017 Euskirchen, et al., 2016 Christie, et al., 2015	10
Permafrost	Christensen, et al., 2019 Natali, et al., 2019 Turetsky, et al., 2019 Wang, et al., 2019 Anthony, et al., 2018 Knoblauch, et al., 2018 Aalto, Harrison and Luoto, 2017	Chadburn, et al., 2017 Euskirchen, et al., 2017 Parmentier, et al., 2017 Piao, et al., 2017 Oledeldt, et al., 2016 Schädel, et al., 2016 Schuur, et al., 2015	14
Lower latitude weather	Post, et al., 2019 Coumou, et al., 2018 Francis, Varvus and Cohen, 2017 Sévellec, Fedorov and Liu, 2017	Chen, Zhang and Alley, 2016 Coumou, Lehmann and Beckmann, 2015	6
Arctic communities	Ford, et al., 2019 MacDonald and Birchall, 2019 Richter-Menger, et al., 2019 Sankar, Murray and Wells, 2019	Sisneros-Kidd, et al., 2019 Hjort, et al., 2018 Ford, et al., 2015	7
Arctic policy	Hansen-Magnusson, 2019 Overland, et al., 2019 Ibarguchi, Rajdev and Murray, 2018	Forbis and Hayhoe, 2018 Seneviratne, et al., 2018 Seneviratne, et al., 2016	6

Implications for the global climate system

Sea-ice cover and land ice loss

Decline of sea-ice in the Arctic region is connected to human-induced climate change and affects life and ecosystems in the Arctic. There is rising evidence of effects on lower latitude weather (Screen, et al., 2018). Only seven percent of the Earth surface is covered by sea-ice, but it is of great importance in the climate system (Screen, et al., 2018), not only in the Arctic. Notz and Stroeve (2016) observed that Arctic sea-ice loss follows CO_2 emissions, noting that there is a linear connection between the extent (million Km_2) of September sea-ice and increasing CO_2 emissions. The extent of sea-ice changes over the course of a year and acts as a barrier between ocean and atmosphere, have a cooling effect as less solar radiation is absorbed in the ocean and is of great importance for indigenous communities by means of transport and hunting (Perovich, et al., 2019). Sea-ice extent is often monitored and measured through satellite instruments (Perovich, et al., 2019), but rising evidence shows that there is a lack of in situ measurements during the winter season, which is proving to be a gap in the research (Gerland, et al., 2019).

New research shows that the changes to Arctic sea-ice differs greatly depending on a temperature rise of 1.5°C or 2°C (IPCC, 2018, 3.3.8). Sea-ice decrease resulting in an ice-free Arctic Ocean is lower for the 1.5°C scenario than for the 2°C scenario during the summer season (IPCC,2018, 3.3.8; Screen, et al., 2018). Under a 1.5°C temperature rise the ocean will be ice-free once every century and for a 2°C rise once every decade (IPCC, 2018, 3.3.8).

Loss of Arctic sea-ice is occurring during all months of the year, with greater magnitude during the summer season, and a negative trend can be observed for all months during the past 40 years (Post, et al., 2019), clearly showing that sea-ice retreat is not simply due to year-to-year variability (Notz, et al., 2020). The 12 lowest summer ice extents have all taken place during the last 12 years. As the older and thicker ice thaws the younger ice is more exposed to summer melting (Richter-Menge, et al., 2019). According to Richter-Menge et al. (2019), during 2018, the sea-ice was both younger and thinner than previously, and was covering a smaller area. As for the sea-ice during winter season it was showing the second lowest extent in the satellite record (39 years). With the previous record low being winter 2017 (Richter-Menge, et al., 2019). As of March 2018, 77% of the ice cover consisted of thin first year ice compared to 55% in the 1980s (Perovich, et al., 2019). This transition to younger ice which is more vulnerable to melting is thus contributing further to the minimum extent of sea-ice during September (Perovich, et al., 2019). A study from Notz et al. (2020) indicates that the Arctic sea-ice will continue to decrease and result in an ice-free Arctic Ocean before the year 2050, defined as when the monthly mean September ice will cover an area less than 1 million km^2. They further show that the observed relationship between winter sea-ice and cumulative CO_2 emissions will continue (Notz, et al., 2020).

Temperature increase resulting in an ice-free summer in the Arctic Ocean would have affects beyond the Arctic region (Post, et al., 2019). The increase of CO_2 is one of the main factors for the decline in sea-ice, which is further enhanced through the feedbacks it produces (Notz and Stroeve, 2016) and contributes to the low extent of sea-ice during summer season.

Not only sea-ice is showing a decline, but snow cover is too. The long-term terrestrial snow cover is declining, with the snow cover extent during June being approximately half of what it was 35 years ago (Richter-Menge, et al., 2019). A decline that almost is in line with the sea-ice loss during September. Due to the reduction of sea-ice, more water is evaporating from the Arctic Ocean and increasing precipitation (Bintanja and Andry, 2017). Despite an increase in precipitation, the snow falling in the Arctic is decreasing. Furthermore, rainfall will become dominant by the end of the century (2091-2100). An increase in precipitation is expected to lead to more snow, but if a rise in the temperature of the atmosphere occurs it will be reduced. Thus, parts of the snow will risk melting before reaching the ground (Bintanja and Andry, 2017). Local and seasonal variability is further complicating the ability to forecast how warming of the Arctic will affect the amount of snowfall. An increase in rainfall in combination with a reduction in snowfall becomes a feedback to further climate change as rain enhances permafrost melt (Nilsson, Polvi and Lind, 2015). Permafrost degradation in anaerobic wet areas risk releasing methane to the atmosphere. Rainfall further has consequences for both ecosystems and large herbivores for which increased precipitation in the form of rain freezes at the ground and complicates grazing (Post, et al., 2019).

Sea level rise due to Greenland ice sheet melt

The loss and melting of the Greenland ice sheet has been one of the big contributors to global sea level rise (Shepherd, et al., 2020), as the ice sheet is affected by the global temperature rise and AA. Estimates show that the ice sheet will continue to lose mass during the 21th century, even if the temperature rise is limited to 2°C above pre-industrial levels (IPCC, 2018; Pattyn, et al., 2018). The continued shrinking of the ice is expected to continue at the same rate as recent decades. However, greater mass loss might still occur as nonlinear responses can not be excluded (Pattyn, et al., 2018) and as the rate of loss is highly variable in nature (Shepherd, et al., 2020). This highlights the importance of including the annual variability in the models.

Instabilities in the ice sheet, or tipping points, might occur at or close to 1.5°C-2°C temperature rise and could result in irreversible loss (IPCC, 2018; Pattyn, et al., 2018). As the Arctic summer air temperature is expected to continue its increase, this could further establish irreversible loss of the Greenland ice sheet (Overland, et al., 2019). The effects would continue during the rest of the century and could in combination with Antarctica ice sheet loss result in a sea level rise of several metres in the timespan of a thousand years (IPCC, 2018). Under the RCP 2.6 scenario, sea level rise due to Greenland ice sheet melt will be approximately 24-60 mm by 2100 (IPCC, 2018).

During most of the period 1992-2018 the Greenland ice mass has been decreasing. For the years 1992 to 2012 the ice loss increased, and reached 345 ± 66 Gigatonne yr^{-1}. But since 2012 there has been a shift and the rate of ice loss has decreased, with an annual rate of loss at 85 ± 75 Gt yr^{-1} by 2018 (Shepherd, et al., 2019).

The modelling of long-term changes with ice sheets has improved in recent years, as it has become easier to simulate the present-day state of the ice sheet (Goelzer, et al., 2017). However, Goelzer et al., (2017) still find challenges in combining observations and at the same time include long-term processes to create modern ice sheet conditions. Simulations of future change is sometimes undertaken in the Coupled Model Intercomparison Project phase 5 (CMIP5). Recent studies, however, indicate that important factors affecting the ice sheet will be excluded in the use of CMIP5 (Golledge, et al., 2019), something that will have implications for future model scenarios.

Effects on lower latitude weather

A continued Arctic warming reaching over the 21th century will have environmental implications globally and will not be constrained to higher latitudes (Post, et al., 2019). Due to Arctic amplification and the greater warming of the Arctic, an expansion of warm air in the atmosphere will occur and thus reduce poleward height gradients (Coumou, Lehmann and Beckmann, 2015; Francis, Vavrus and Cohen, 2017). These gradients are important factors in zonal winds, and, when weakened in combination with higher atmospheric pressure due to AA, affect the polar jet stream. When affected, it risks increasing both warm and cold extremes (Francis, Vavrus and Cohen, 2017). Studies indicate that AA in combination with some natural variabilities in the climate system influence persistent weather patterns with extremes over Asia, which may experience cold outbreaks and heavy snow fall (Francis, Varvus and Cohen, 2017). However, natural fluctuations in the atmosphere and the fact that the onset of rapid AA has emerged recently creates difficulties in projecting how the jet stream will be affected (Francis, Vavrus and Cohen, 2017).

The Arctic's effect on lower latitude weather is still being debated, but is often centered on winter weather. However, both AA and the decline of sea-ice may influence extreme weather during the summer season in the Northern Hemisphere (Coumou, et al., 2018). An increase in extreme summer temperatures has been observed in Europe during the last decade as well as the highest recorded extreme temperature, occurring in 2010 (Coumou, et al., 2018). Extreme weather events will become more frequent in Europe during the boreal summer, and risk for droughts, heat waves and floods will increase (Hoffmann, 2018), as seen in anomalous extremes in 2018 (Post, et al., 2019).

One of the ways in which the Arctic region affects lower latitudes is changes in ocean circulation due to greater exposure of the ocean to surface heat and radiation as a result of sea-ice loss and increases in freshwater flux due to ice sheet melt. This will lead to a weakening of the Atlantic Meridional Overturning Circulation (AMOC) (Sévellec, Fedorov and Liu, 2017), which is also projected to continue in a future with warmer climate as seen in Figure 4. (Coumou, et al., 2018). A slow-down of AMOC would in turn decrease the oceanic heat transport to lower latitudes and the subtropics. Thus, the Arctic Ocean is of great importance for the changes in climatic conditions in the North Atlantic (Sévellec, Fedorov and Liu, 2017). This relationship between the Arctic Ocean and North Atlantic climate is of complicated sort and would result in a local cooling of the mid-latitude region superimposed on the global warming signal, being a negative feedback effect. However, it could also, through a weakening of the westerlies, lead to high extremes in temperature during the European summer (Coumou, et al., 2018).

However, a study by Chen, Zhang and Alley (2016) shows conflicting results. They suggest that the link between changes in lower latitude weather and decline in Arctic sea-ice is a result of several factors corresponding to each other, like the climate variability, and not only due to AA and reduced poleward height gradients. The connection between sea-ice decline and changes in mid-latitude weather patterns is complex and different studies show different results (Chen, Zhang and Alley, 2016). In observational studies, short time series and high variability makes robust results difficult to arrive at. In modeling studies, several factors may influence the result, such as the model used in the study and the model version (Chen, Zhang and Alley, 2016). This complicates the matter of comparing contradicting results. Although there is rising consensus that a warming Arctic will affect Northern Hemisphere weather, both natural and anthropogenic stressors make it uncertain how it will change and in what timespan (Francis, Vavrus and Cohen, 2017).

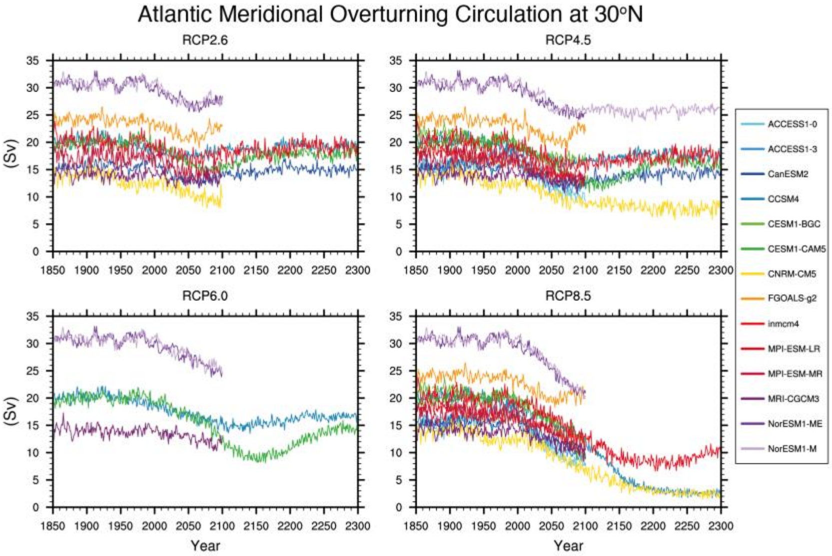

Figure 4. The Atlantic Meridional Overturning Circulation at 30°N to the end of the RCP scenarios timespan, using different climate models (shown in different coulors). Source: IPCC, 2013, Figure 12.35.

Ecosystems and Vegetation dynamics

As the Arctic region is exposed to increased temperatures, its vegetation and ecosystems are affected and change. With the retreat of the Arctic tundra (Liu and Xue, 2020), the vegetation area is expanding. To a greater extent, ecosystems dominated by shrubs and trees in the Arctic tundra are expanding ecosystems and generating positive feedbacks, further enhancing the warming (Liu and Xue, 2020). For the years 2015-2050 models indicate a projected decrease of the Arctic tundra of 17,000 km$_2$/year (Liu and Xue, 2020), making this land area available to Arctic greening.

Studies show evidence that the greening is due to both increased temperatures during all seasons in combination with an increase in the growing season length (IPCC, 2019), as well as CO_2 fertilization (IPCC, 2018). A continued warming and climate change will alter species composition, land cover, drainage, and the extent of permafrost, all of which are related to vegetation extent in Boreal-Arctic (IPCC, 2014a). An increase or overall change in the tundra vegetation will affect the carbon cycle and energy exchange between soil and atmosphere. Moreover, it will be of significance for the active layer of the permafrost areas, thus affecting both ecosystems and infrastructure (Richter-Menger, et al., 2019). This acceleration of warming connected to latitude may also be the reason for greater phenological change at the same latitudes (Post, Steinman and Mann, 2018). An earlier growing season might benefit some species whilst some phenological responses have negative implications for ecosystem functioning when the timing of species interactions is altered (Post, et al., 2019), such as a shorter flowering period not coinciding with pollinator lifecycles. Phenological changes may also lead to a decline in Arctic specialist species and a reduction of suitable habitats for such species as competition with other species increases when they expand from boreal habitats (Fauchald, et al., 2017; Wheeler, Høye and Svenning, 2018).

Although the land may be available for vegetation expansion, it is important to mark that several factors decide whether a tree species expands into the Arctic tundra. Brown et al. (2019) show that a complex combination of climatic conditions determines a shift in the treeline. A warming Arctic opens new ecologic niches to be filled by species and new conditions that may be favorable for germination, but may not result in the species filling the new niche (Brown, et al., 2019). These complex requirements are supported by the fact that the treeline is not expanding uniformly in a response to climate change (Brown, et al., 2019). Recent projections of the tundra retreat, however, show how the Arctic tundra will be reduced northward 60 km in North America and 40 km in Eurasia (Liu and Xue, 2020), by the year 2050. Thus, allowing for a greening in the post-tundra area. The vegetation expansion is not limited to trees but is dominated by shrubs, called the "shrubification" of the Arctic (IPCC, 2019). This change in shrub cover will affect both ecosystems and wildlife through both population densities and grazing (Wheeler, Høye and Svenning, 2018).

Arctic warming with higher temperatures and changed soil moisture will result in the tundra in Greenland turning into a homogenous one only holding a number of vegetation species due to shrubification (Christie, et al., 2015; Stewart, et al., 2018). This may have a positive climate feedback effect as the albedo is reduced when snow cover is lost, but might result in a higher number of wildfires linked to the shrubification (Euskirchen, et al., 2016). The mechanisms leading to expanding shrub in the Arctic tundra may thus have consequences for the climate on both a local and global scale (Stewart, et al., 2018).

Vegetation dynamics are influenced to a great extent by large herbivores in the Arctic region (Post, et al., 2019). A warmer climate affects the herbivores and further also the ecosystem. Preferential grazing on taller plants enables low-growing plants to grow and not be overwhelmed by competition with taller plants. Thus, interaction with herbivores helps to keep the biodiversity and increase species richness (Kaarlejärvi, Eskelinen and Olofsson, 2017), something that otherwise would decrease with increased warming. A decrease in diversity could follow from a loss of herbivores in the tundra region during climate warming. The decrease would be greater in areas of high productivity and protecting the herbivores would mitigate climate warming on a local scale, preventing diversity decrease (Kaarlejärvi, Eskelinen and Olofsson, 2017). However, an increase in plants containing an anti-browsing defense, such as resins or toxins, gives them an advantage over other plants and might instead not be controlled by herbivore population (Fauchald, et al., 2017). Furthermore, some plants may be more preferred by herbivore species. Deciduous shrub will respond faster to a warmer climate and expand, whereas evergreens more often contains some form of anti-browsing defense and is thus avoided (Christie, et al., 2015).

It is important to research herbivore response to climate change due to their ability to affect vegetation dynamics and shrubification. Despite the relationship being of great importance some of the dynamics are still unknown, and the effects herbivores may have on vegetation is closely linked to densities, behavior and distribution of both free and managed animals along with plants (Wheeler, Høye and Svenning, 2018). Wheeler, Høye and Svenning (2018) did not find any positive response to shrubification in species exclusively located in the Arctic, which could be linked to the greater extent of boreal habitats. Further, they could conclude that a number of the species included in the study had an overall positive response to an expansion of shrub, indicating that further research of its effects is needed.

Permafrost thaw

About one-quarter of the soil in the Northern Hemisphere is frozen as permafrost, holding twice as much C as the atmosphere (Turetsky, et al., 2019). Thawing permafrost risks increasing the thickness of the active layer - the layer thawing and re-freezing each year - thus affecting the natural drainage of the area (Schädel, et al., 2016). With rising temperatures, the active layer will increase, as the thawing makes organic C available for decomposition (Euskirchen, et al., 2017).

Thawing permafrost not only releases GHG from the tundra, the frozen soil holds the landscape together. Without the permafrost the soil risks abrupt collapse. Increased warming can destabilize metres of soil faster than an otherwise slow thaw of the top soil (Turetsky, et al., 2019). Contemporary models calculating GHG emissions only take into account thaw occurring from the top soil down (Turetsky, et al., 2019), making the potential impact from thawing permafrost considerably more extensive than previously calculated. This abrupt thaw will not occur everywhere in the permafrost area, but projections indicate it will increase release of carbon from the soil by up to 50% (Turetsky, et al., 2019). The process occurs as ground ice melts, and the soil collapses into the area that contained ice (Schuur, et al., 2015). The collapsed permafrost soil is called thermokarst, which is calculated to cover 20% of the permafrost area (Olefeldt, et al., 2016).

Thermokarst has the potential to damage Arctic infrastructure in addition to affecting local hydrology and ecology (Olefeldt, et al., 2016). The collapsed thermokarst may be colonized by plants, offsetting the carbon loss and stabilizing the soil (Turetsky, et al., 2019). After surface collapse, water may fill the collapsed area, creating taliks underneath lakes. Increased rate of permafrost thaw would follow, compared to thaw linked to temperature rise (Anthony, et al., 2018). The number and magnitude of lakes which taliks can form under will depend on if the climate gets wetter or drier. Models indicate that wetter conditions are to be expected with a higher rate of precipitation during the Arctic summer, thus creating conditions for thermokarst lakes to evolve and expand (Anthony, et al., 2018). The drier or wetter conditions in the Arctic as a consequence of warming will affect the amount of C to be released (Schädel, et al., 2016). A fragmented landscape of wet and dry areas is to be expected, making the projections for C release uncertain. But the Arctic warming is expected to affect dry soils to a greater extent (Schädel, et al., 2016). It is further relevant if the thaw is occurring in anaerobic or aerobic environments, deciding how much and in what form C – CO_2 or methane (CH_4) – is to be released (Schädel, et al., 2016). The amount of CH_4 released depends on changes in the physical environment in the form of permafrost changes and thermokarst formation, the amount of C that is available in the soil, and temperature and precipitation in the Arctic (Christensen, et al., 2019). During aerobic conditions the stored carbon will be oxidized to CO_2, but during anaerobic conditions- which often are the case with wetter soil, both CO_2 and CH_4 will be formed (Christensen, et al., 2019; Knoblauch, et al., 2018). Thus, permafrost thaw which exposes organic soil to air will cause a greater release of CO_2 to the atmosphere, but a combined release of both CO_2 and CH_4 will greatly enhance its global warming feedback (Christensen, et al., 2019). Simulations show that though CH_4 only represents 20% of the carbon emissions from permafrost soil, it has higher global warming potential (GWP) than CO_2 and thus makes up 50% of the radiative forcing related to abrupt thaw of permafrost (Turetsky, et al., 2020). However, an earlier study by Schädel et al. (2016) showed contradicting results through a warming experiment where the amount of C released from permafrost soil was greater under aerobic than under anaerobic conditions. The same results were achieved even when incorporating the higher GWP of CH_4.

The Arctic is thus a source but also a sink for greenhouse gases. However, there is insufficient data to determine whether the Arctic is currently acting as a sink or a source (Euskirchen, et al., 2017). A warming climate is expected to change the amount of C stored in and emitted from both Arctic soil and vegetation (IPCC, 2019). Loss of CO_2 from soil is enhanced due to warming and may even offset extra carbon uptake during the growing season (Natali, et al., 2019), if temperatures and CO_2 fertilization keep rising. The loss of sea-ice and the following warming of the Arctic is expected to affect the terrestrial carbon cycle, risking influencing the warming trend further through changes in vegetation and enhanced permafrost thaw (Parmentier, et al., 2017). Research on spring carbon uptake in northern areas by Piao et al. (2017) shows that extensive in situ measurements of CO_2 are often is needed to fully comprehend the response of carbon balance to climate change. Research has further shown that permafrost thaw will follow GHG emission induced climate change, but the extent of permafrost degradation is still largely unknown (Wang, et al., 2019). The permafrost degradation is also subject to regional variations, due to differences in soil type, extent of the permafrost area and different thicknesses of the active layer (Wang, et al., 2019).

The impact of the carbon released due to permafrost thaw is estimated to affect the climate, on a global scale, for centuries. Models are suggesting that up to 59% of the carbon emissions from permafrost areas is due to be released after 2100 (Schuur, et al., 2015). Model scenarios show that stabilizing the temperature at 2°C above pre-industrial levels will reduce the permafrost area by 40%. A stabilization occurring at 1.5°C would instead prevent an area of 2 million km_2 from thawing, compared to 2°C (Chadburn, et al., 2017). The changes in permafrost area are shown in Figure 5 for the different RCP scenarios. Aalto, Harrison and Luoto (2017) show that despite mitigation policies in place to combat climate change, decay of permafrost areas which have modified the landscape will continue in high speed by the end of the 21th century.

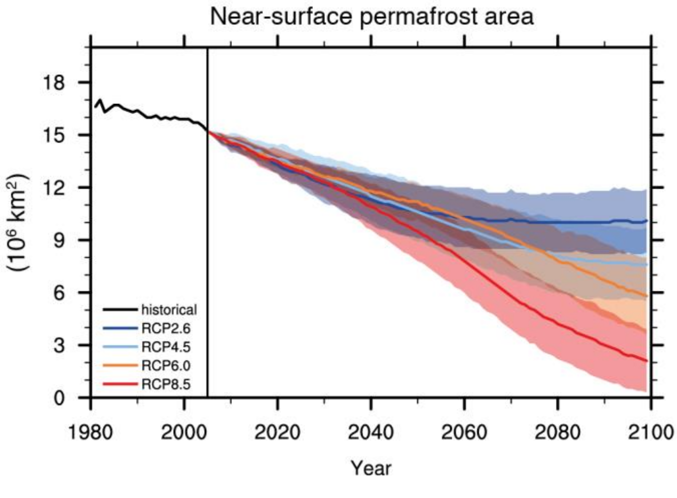

Figure 5. Near-surface permafrost area changes for IPCC’s RCP scenarios. Source: IPCC, 2013, Figure 12.33.

Arctic communities

The Arctic communities are highly vulnerable to global climate change, as both the rate and extent are affecting them and how adaptable they are (Ford, et al., 2015). Studies have shown that there is a great adaptation capacity amidst the Arctic community and that collective efforts may reduce the climate risks (Ford, et al., 2015). The adaptability can be observed in the resource use of the Arctic communities, as their means of obtaining food has often been subject to variable and unpredictable climate variations. However, these abilities are becoming restrained as they do not fit into modern societal changes and recent developments in land use (Ford, et al., 2015). To increase the resilience of the Arctic communities it is paramount to implement long-term policies for adaptation (MacDonald and Birchall, 2019). A successful resilience-building is dependent on a collaboration with local stakeholders to ensure that the views of Arctic communities are represented, potentially resulting in immediate action as the stakeholders often have more insight into which vulnerabilities the community experiences (MacDonald and Birchall, 2019).

A warming Arctic region may force communities to alter their way of living, depending on other sources of income. The reliance on nature-based tourism could increase in line with the global tourism and at the same time reduce the resilience of the communities and increase their vulnerability (Sisneros-Kidd, et al., 2019). Tourists exploring the Arctic region before it is altered by climate change, “last-chance tourism”, makes Arctic communities dependent on the tourism that is subject to cycles of higher or lower activity (Sisneros-Kidd, et al., 2019).

The means of transportation will also be influenced by Arctic climate change (Ford, et al., 2019). Trails on land, water and sea-ice, which in some cases are the main trails for Arctic communities, are being altered and some are becoming less accessible (Ford, et al., 2019). How the trail is influenced by altered conditions depends on the type of trail. Ice trails are highly influenced due to changing ice concentrations, and modelled scenarios show a significant decline, whereas access to land trails are unaltered (Ford, et al., 2019). Further, usage of land trails allows more transportation mode options which makes communities that more frequently use those trails over others less sensitive to impacts of a warming Arctic (Ford, et al., 2019). Those communities reliant on declining trails may choose different routes, which negatively impact the often cultural and food-related use of ice (Ford, et al., 2019). However, the study by Ford et al. (2019) showed that skills and knowledge of the communities were dominant in choosing trails rather than changing conditions due to climate change (Ford, et al., 2019), demonstrating the high adaptive capacity of the Arctic community (Ford, et al., 2015).

Not only trail access is influenced by the Arctic warming, but it is also putting infrastructure at risk. Up to 70% of infrastructure in permafrost areas is at risk from permafrost thaw by 2050, implying that Arctic infrastructure will be under risk despite achieving mitigation targets under the Paris Agreement (Hjort, et al., 2018). An ambitious decrease in GHG emissions will not make a substantial difference for infrastructure located in high risk zones by 2050, as even the ambitious RCP scenario (2.6) expresses similar effects. This will affect 3.6 million people in the permafrost area in the Northern Hemisphere, showing potential risks for fundamental human infrastructure, human residents, railroads and pipelines (Hjort, et al., 2018). During 2018 there was an absence of ice in the Bearing Sea which affected the coastal communities living there. They grew more vulnerable as the lack of ice led to coastal erosion and exposure to winter storms that the ice would otherwise serve as a sheltering barrier against (Richter-Menge, et al., 2019). A case study conducted by Sankar, Murray and Wells (2019) on coastal degradation in Paulatuk, Canada, indicates that elevated air- and surface temperatures have led to permafrost thaw and a decline in sea-ice affecting the coastal area and causing coastal erosion. This is occurring in an area which, compared to other Arctic coastlines, historically has seen low rates of long-term change. The study further states that the adaptive management practices to be used, should to a great degree be community-led using in-situ observations to predict and prepare for a continued change in the coastline and to protect infrastructure (Sankar, Murray and Wells, 2019).

Despite considerable risk even under mitigation scenarios, the temperature targets of the Paris Agreement have the potential to further limit damage beyond 2050 (Hjort, et al., 2018). Thus, a sustainable development in the Arctic depends on both local and regional mitigation measures and requires that vulnerable infrastructure is identified and approached with measures adapted to the changing conditions (Hjort, et al., 2018).

Policies regarding Arctic change

The connection between CO_2 emissions and the observed changes in the global mean temperature has made it evident to the public how the climate system responds to emissions and disturbances (Seneviratne, et al., 2016). The difficulties now lie in translating it into actions as the global implications do not easily translate into regional and local changes and consequences (Seneviratne, et al., 2016). Further, the consequences at a regional and country level regarding projected global mean temperature often tend to be underestimated as the global changes are often smaller than that of regional ones over land (Seneviratne, et al., 2016). It is easier for both decision makers and local stakeholders to relate to regional and local changes in temperature than global changes. Seneviratne et al. (2016) point out that this in no way indicates that the informed policy makers show less care for the changes that are global and not affecting them, but rather makes it easier to make decisions when knowing which implications to be expected for each region.

The variations in both the pace and location of climate change makes it clear that even if the United Nations Paris Agreement's ambitious goal of a 1.5°C warming above pre-industrial levels is reached, the changes and risks, will not be universal in all locations (IPCC, 2018). This implies that on a regional scale the vulnerability will change and ultimately that policies consistent with the 1.5°C goal cannot be considered the same globally (Seneviratne, et al., 2018). The risks associated with regional warming must be considered when making policy choices. It is also important to have the timeframe in mind when making decisions. Seneviratne et al. (2018) indicate that to achieve maximum mitigation efforts in limiting the warming to 1.5°C or 2°C compared to pre-industrial levels, the reduction of GHG emissions has to start immediately and result in an observed decline by no later than 2020 (IPCC, 2018). Moreover, development of the use of the Arctic Ocean following Arctic change will affect policies. An ice-free ocean will likely result in countries referring to the freedom of navigation, and further discussions relating to the use of the Northwest Passage (Hansen-Magnusson, 2019). There is no uncertainty as to whether the Arctic and its climate will change or not, as it has already (AMAP, 2017), it is rather the extent of change and the effects on local regions that remains uncertain (Overland, et al., 2019).

Arctic policy and sustainable development in the Arctic is the responsibility of the Arctic Council (Hansen-Magnusson, 2019), consisting of 8 countries. The council is unique in its inclusion of 6 representatives of indigenous populations in the Arctic, naming them Permanent Participants of the council. The Permanent Participants have no right to vote or participate but inherit the right to veto initiatives (Hansen-Magnusson, 2019) and thus occupy a strong position in representing the opinions of Arctic residents. This combination of state and non-state actors interrelate the division of responsibility (Hansen-Magnusson, 2019). The council is using soft law with non-legally binding elements but negotiates binding agreements (IPCC, 2019). However, Forbis and Hayhoe (2018) demonstrate the problematic aspects of Arctic policy being driven by countries with their own definition of sustainable development, agendas and drive for domestic resource development. Instead they advocate for Arctic energy policy being framed by the Arctic council and a greater inclusion of the scientific community. Compared to other nations, the governing body of the Arctic council is unique, as it consists of scientist from several member states holding the policymaking positions (Forbis and Hayhoe, 2018). It is clear that up to this date, Arctic questions have not been prioritized which can be recognized through the lack of funding needed for research to make evidence-based decisions (Ibarguchi, Rajdev and Murray, 2018).

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Discussion

The recent trend with enhanced Arctic warming and Arctic amplification is expected to continue and further GHG emissions will result in a continuous decrease in sea-ice extent (Notz and Stroeve, 2016), snow cover (Bintanja and Andry, 2017), a shrubification of the Arctic tundra (IPCC, 2019), irreversible changes to the Greenland ice sheet (IPCC, 2018), and further permafrost degradation (Schuur, et al., 2015). By the end of the century, an ice-free summer in the Arctic might become the norm. There is no longer much of a debate as to whether Arctic amplification is occurring, but rather to what extent, how the changes will occur, and how quickly. Even with extensive mitigation efforts, the Arctic as we know it will change. As an important part of the global climate system and a regulatory agent of the global temperature, this will have wide implications.

Research progress

The results acquired in this thesis indicate that the research and knowledge of Arctic feedback effects has changed since the publication of SWIPA 2017. In SWIPA, several feedback effects were identified as fields which were subject to further studies, and inherit potential to affect AA and has global implications for people and resources, as well as social, economic and political factors (AMAP, 2017). The feedbacks researched in this thesis was included in the SWIPA report and has undergone changes since 2015. When comparing the results found here with the conclusions in SWIPA, it is evident that some of the Arctic changes seen to date have been predicted and projected years ago, but the pace at which the changes are occurring is faster than expected. No matter which one of the future emission scenarios presented by the IPCC is followed, the Arctic is still projected to change in ways and at a pace never seen before in the historical records, both in terms of snow cover, permafrost, and in changes to the Arctic ecosystems (Overland, et al., 2019). Further, the inclusion of the feedback effects in climate models is an important step towards future projections of climate change. As shown in Table 4, the research acquired in this thesis is heavily tilted towards sea-ice and snow cover changes, changes in Arctic vegetation dynamics and permafrost. Although the number of articles represented in this thesis is limited, this indicates that these fields are of focus in recent research. This could be due to the identification of these fields as potential contributors to greater climate change and illustrates important advances in recent years. Further, decrease of the Arctic tundra and following shrubification has potential to store CO_2 and could therefore be an area of interest and scientific expansion, as well as the risks for human systems and infrastructure, and GHG release associated with permafrost thaw. Another explanation can be the search words and combination used in the thesis. Several searches explicitly used the word permafrost and can thus explain the high number of articles on the subject, which cannot be said about sea-ice and vegetation dynamics. However, this does not explain the relative low amount of research found on sea level rise and effects on lower latitude weather. The new socioeconomic pathway and emission scenarios with a radiative forcing of 1.9 W/m_2 instead of the previous lowest RCP emission scenario of 2.6 W/m_2 (RCP 2.6) enables scenarios in recent research in which the mitigation efforts are more extensive and allows a more optimistic view of Arctic future than previous. Thus, having implications for Arctic policy which are more extensive than those presented in SWIPA. Noteworthy is the difficulties in comparing results from some of the studies represented in this thesis with the future projections of SWIPA, which primarily used the RCPs 4.5 and 8.5 (AMAP, 2017).

The pace of change can be observed in the changes between SWIPA 2017 and new research. It was previous stated that substantial cuts in GHG emissions could stabilize climate impacts after 2050. Moreover, following the scenarios of the Paris Agreement was predicted to stabilize both permafrost and snow, preventing further loss (AMAP, 2017). Recent research indicates that even if the Paris Agreement target of <2°C rise compared to pre-industrial levels is met, this means that the changes in the Arctic may complicate the stabilization of the global climate after that. The coming years will be of great importance to determine which of the simulated paths current emissions will follow. Emerging evidence shows that tangible mitigation regarding GHG emission release must commence and rapidly decline during 2020 to avoid irreversible change (IPCC, 2018; Seneviratne, et al., 2018).

Arctic implications

Perhaps the most prominent change, which is known to the greater public, is the loss of sea-ice. The loss will not only affect the marine ecosystems and the Arctic communities using the ice for hunting and transport, but will also influence the atmospheric and oceanic circulation and to some extent induce changes in lower latitude weather. The linear connection between GHG emissions in the atmosphere and loss of sea-ice makes it evident that there will be a continuous decrease in sea-ice extent if substantial mitigation efforts are not in place to make a marked decline in GHG emissions. However, there is no evidence that the loss of Arctic sea-ice would be irreversible, which would indicate that changes in sea-ice extent and thickness have the potential to be reversed and recover under a suitable climate (IPCC, 2018). This implies that in the case of an overshoot from the scenarios of the Paris Agreement during the 21th century, it is still possible for the sea-ice to recover by the end of the century. As for sea level rise, the connection to warming and AA is likewise evident. Limiting the warming to 2°C will still result in a loss of some of the Greenland ice sheet during the 21th century. Due to the lag in some climate responses, the changes will be continuous during the century.

For some vegetation and animal species, increased warming may be favorable, allowing boreal species to expand to the Arctic tundra. This would alter the Arctic's ecosystems and vegetation dynamics but might open niches for other species than Arctic specialists. Evidence suggests that a shrubification of the tundra is occurring and will continue, making the tundra more homogenous and dominated by low-growing shrubs. It is a matter of scientific debated whether or not large herbivores can be used for ecological and climate engineering, allowing for certain plant species to thrive in the tundra. It is also debated whether this greening of the Arctic has the potential to offset CO_2 released from permafrost thaw, but more research is needed. It may to some degree reduce the CO_2 in the atmosphere, but the permafrost degradation is projected to be extensive under both the 1.5°C and 2°C scenarios. As one quarter of the Northern Hemisphere soil consists of permafrost, this would imply the potential for large amounts of CO_2 to be released to the atmosphere and a collapse of soil and infrastructure when the permafrost soil is exposed to microbial degradation. Holding twice as much CO_2 as the atmosphere, further research is needed to outline the pace and extent of the thaw. Since SWIPA 2017 permafrost thaw has occurred faster than predicted and several cases of thermokarst formation have occurred, indicating that abrupt thaw is becoming more frequent. The biogeochemical effects of abrupt thaw will be considerable, releasing a greater amount of CO_2 under a shorter interval. It will likely heavily affect the Arctic communities and the population living in permafrost areas, as both human infrastructure and hydrology will be altered. Thaw in coastal areas will lead to further risk of coastal erosion, making Arctic communities increasingly vulnerable. Supplementary damage to the Arctic and mainly Arctic ecosystems could be the result if the permafrost thaw was to affect the pipelines located in permafrost regions, having devastating consequences.

The rate of warming, and if the aim of 1.5°C and 2°C is reached before or after 2100, will largely influence the amount of risk associated with warming. There is also a risk of overshooting the target, which does not indicate that the temperature will not reach the desired levels post-overshoot. Implementation and development of policies and mitigation measures are needed. Since the changes are too great to be solved by a single nation the efforts must be addressed through multinational cooperation (Post, et al., 2019). Rising evidence shows that the changes in the Arctic will not stay in the Arctic, but will influence middle latitudes through both oceanic and atmospheric circulation. Sea-ice extent regulates the amount of solar radiation to be absorbed, as an ice-free Arctic ocean inherits a lower albedo and thus absorbs more energy than the white, reflective sea-ice surface with a high albedo. This affects both the atmospheric and oceanic circulation and could lead to a considerable increase in extreme weather at lower latitudes, such as floods, heat waves and extreme winter cold. Some studies indicate that the changes seen in the Arctic are the reason for the extreme summer temperatures experienced during European summer in recent years. However, further research is needed in this area to establish the effects on lower latitudes and globally. It is not unusual that conflicting results arise from studies of impacts outside of the Arctic region. It is important to keep a critical approach to all studies to avoid bias and thus recognize that different models can show different results depending on several factors. An observation-based model will be limited to the collected observational data whereas simulation based projections will differ in which type of model is used. Nevertheless, there is rising evidence that Arctic change will continue and have far-reached effects over the globe.

Social, political and resource aspects

The current changes in the Arctic will affect the way of living for Arctic communities. Their means of transportation will be altered with permafrost thaw reducing availability to roads and the sea-ice decline limiting the number of sea-ice trails to use. As the sea-ice declines, this increases the availability of the Arctic Ocean for passage (Perovich, et al., 2019), which is something that might make the Arctic more accessible, and which could become an element of conflict and marine pollution. Sources of income will be affected and a greater transition to nature-based tourism might, instead of securing income, further reduce the community’s resilience. As the infrastructure is under risk from thawing ground, this will affect 3.6 million people living in the permafrost area in the Northern Hemisphere. A reduction of vulnerability for the Arctic communities will be achieved through the implementation of long-term adaptation measures. Furthermore, local stake-holders should be included in the decision making and community-led initiatives should be prioritized, thus including the views and knowledge of the community itself. Studies imply that Arctic communities have a great adaptation capacity, and will therefore have the capability to manage an amplified warming, which will depend on both local and regional adaptation and mitigation efforts. Despite the general adaptability, some limitations to adaptation are shown in studies, indicating the difficulties with rapid climate change. The adaptability of Arctic communities seems to be the product of direct experience of climate change and altering conditions, traditional knowledge being inherited, and to some extent the ability to change their resource use and sources of income.

The level of climate related change will not be universal in all locations over the globe. More extensive policy measures are needed in the Arctic which is experiencing a temperature rise two to three times that of the global average. Thus, the policy implications will be specific to the Arctic alone. The fact that the Arctic is not a nation but governed by the countries of the Arctic council and its permanent participants creates a unique situation for decision making and policy implementation. However, it also entails great scientific competence from different countries coming together. Arctic change has recently gained more attention and momentum with prominent climate change research (IPCC, 2019; AMAP 2017), having the potential to influence Arctic policy and initiate more forceful mitigation and adaptation efforts.

Conclusion

The objective of this thesis was to identify (I) how the research on Arctic feedback effects had changed since the publication of SWIPA 2017, (II) how the Arctic warming would influence the global climate, and (III) what the 1.5°C and 2°C targets mean for the Arctic in terms of AA, feedbacks and policy. I have through this literature review shown that the Arctic research has gained momentum in recent years, where new studies indicate that changes in the Arctic in some aspects are occurring at a faster pace than anticipated by model simulations. The future Arctic is expected to experience further temperature rise, increased precipitation and a continuous decrease of sea-ice and permafrost. Recent studies even imply that the Arctic Ocean has the potential of being ice-free by the year 2050.

The thesis (I) identifies sea-ice and snow cover, vegetation dynamics and permafrost as research focuses which has emerged and been extended in recent years since SWIPA 2017. Being subject of scientific debate, further research has been conducted in these fields since 2017, allowing for a shift in the literature. The shift in focus implies the rising importance of these feedbacks and their effects, and the efforts conducted to incorporate them into climate models. Without their inclusion in models, simulations of future change will be subject to uncertainties. Being fields of high natural variability, new studies will hopefully close gaps in information and knowledge, and open for more accurate projections.

The results indicate that (II) effects on lower latitude weather are expected to increase in frequency, shown through an increased number of wildfires, floods, extensive droughts and extreme temperatures foremost in Europe, with some effects globally. Moreover, global effects can potentially arise from the Arctic's influence on the Atlantic Meridional Overturning Circulation which would decrease the ocean heat transport to mid-latitudes and the subtropics. However, influence on global weather is subject to further research and not fully comprehended in line with Arctic change.

The Paris Agreement aim of limiting the global average temperature increase to 1.5°C and 2°C compared to pre-industrial levels has the potential to limit damage beyond 2050. Nonetheless, the thesis concludes that (III) due to a lag in some of the climatic responses to enhanced warming, changes in the Arctic are expected to continue during the rest of the century even with extensive mitigation efforts. The Greenland ice sheet will continue to lose mass until the end of the 21th century and beyond, and the sea-ice will decline even with GHG emission reductions. Even if the temperature goals are reached, the Arctic may thus complicate the stabilization of the global climate after that, considering that models do not yet include all the feedback effects. However, the new socio-economic pathway emission scenarios from the IPCC with the lowest radiative forcing are the best scenarios under which Arctic change will be less extensive. Following the emission pathways of the scenarios, the Arctic will still be subject to change. Missing feedback effects, such as permafrost carbon and CH_4 reduce the GHG budget that will meet the 1.5°C or 2°C goals.

Further, (III) the policies implemented in the Arctic have to be specific to the Arctic region alone, as AA is making the regional changes greater than global changes. Thus, policies consistent with the 1.5°C goal cannot be considered the same globally. Being the responsibility of the Arctic Council, extensive adaptation and mitigation efforts are required to increase the resilience and reduce the vulnerability of Arctic communities and limit further climate change. Earlier studies have highlighted the ability of Arctic communities to adapt to climate change and their capacity to influence policy to include the needs and opinion of Arctic populations. However, it seems that the changes are occurring on local level and with a short timeframe. Sometimes the financial aspect becomes a barrier for policy implementation. Research suggests that there must be some barrier for the implementation of extensive adaptation and mitigation strategies. It is possible that the Arctic council requires more authority and the ability to practice something else than soft-law and non-legally binding agreements. However, the multinationality of the council could be problematic in the case of a legally binding element.

More and continuous work is needed to understand and correctly project warming of the Arctic and the effects it will have on the global climate. Knowing the impacts of this expected warming, it is important to put suitable policy measures in place and to conduct extensive mitigation efforts.

Recommendations for future work

In conclusion, the thesis identifies aspects of Arctic policy which needs to be enhanced and implemented to limit Arctic change. In line with the new IPCC SSP scenarios consisting of a lower radiative forcing than the previous RCP scenarios, and the confirmed acceleration of Arctic warming, it is preferable to limit the warming to 1.5°C instead of the aim of 2°C. This recommendation considers the differences in both risk and temperature. It is the view of the thesis and its author that adaptation measures will be more manageable and more easily implemented when done so in an early stage.

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Appendix I

The following list summarizes the number of articles identified in the literature review which was later used in the text. Number in total: 25 articles.

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