*Educate, engage and advocate with the public and policymakers to mitigate climate change to protect global security and natural ecosystems*

**WHITE PAPER**

# PROPOSED: NATIONAL ARCTIC ICE RESTORATION INITIATIVE (NAIRI) PLAN

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## EXECUTIVE SUMMARY

*Global warming (GW) is causing a dramatic shrinking in Arctic sea ice, land ice and snow. A National Oceanic and Atmospheric Administration (NOAA) study reports that the Arctic has warmed more than twice as fast as the rest of the planet, due to a phenomenon known as Arctic Amplification. Arctic warming also drives the thawing of permafrost releasing greenhouse gasses (GHG) from the Arctic land and shallow seabed off the Siberian coast that further accelerates global warming. With loss of sea ice left unchecked, global warming will soon exceed the 1.5°C (2.7°F) target set by the UN Intergovernmental Panel on Climate Change for 2100, resulting in food and water shortages, damage to infrastructures and the environment, mass human migrations, and destabilization of governments, all threatening U.S. national security interests at home and abroad.*

*U.S. national security at home is at risk because of extreme weather patterns and sea level rise linked to Arctic warming impacting our agriculture, infrastructure, and economy. The balance of power in the Arctic region is in transition as Russia is pursuing resource exploitation and shipping in the region. China is also showing increased interest in the region. On the other hand, U.S. military installations and facilities in the Arctic are at risk of significant infrastructure damage resulting from erosion, thawing permafrost, and rising sea levels.*

*We believe the U.S. urgently needs a mitigation strategy focused on preservation and restoration of summer Arctic sea ice to prevent the effects of a warming Arctic from reaching a tipping point. This White Paper proposes to the Biden-Harris Administration that the U.S. establish, in the spirit of a coordinated "whole-of-government approach", a multi-agency effort for an applied R&D program called the "National Arctic Ice Restoration Initiative" (NAIRI). NAIRI is designed to better understand Arctic climate processes and develop approaches to help preserve and restore Arctic sea ice. Further, we believe the U.S. should take the lead in developing and coordinating an international response to mitigate Arctic sea-ice loss and its accelerant effect upon global warming (GW) and the climate change crisis. The DoD identifies GW as a threat multiplier.* Annual funding for NAIRI would notionally be at 2021 levels of appropriate elements of participating Agency budgets ***augmented*** by an aggregated total of $283M over 5 years. *(Please note: this budget is updated from the recent publication "Strawa, A. et al. Arctic Ice Loss Threatens National Security: A Path Forward. Orbis. 10 Aug 2020").*

*Doing nothing to stop the continued warming of the Arctic and the devastating consequences to the world, at home, and to our National security is not an option.*

## 1.0 OVERVIEW

The principals at "Secure the Future 2100" (https://securethefuture2100.org/) respectfully submit this proposal to the Biden-Harris Administration for consideration. Our organization is dedicated to educating, engaging, and advocating with the public and policy makers to mitigate climate change to protect global security and natural ecosystems. Our perspective on the Arctic region is shaped by a deep interest and commitment to preserving and restoring Arctic sea ice, the dramatic and alarming loss of which is amplifying GW and climate change throughout the northern hemisphere and perhaps world-wide. Accordingly, we believe our organization's goals are in alignment with the Biden-Harris Administration commitment in making climate change a whole-of-government approach with a national security and foreign policy priority to slowing down and reversing GW and climate change. We appreciate the opportunity to provide our perspective on research priorities for the Arctic: particularly at a time when the Arctic is in crisis.

This white paper proposes a bold new plan for multiple Federal Agencies to add a major new Arctic Sea Ice restoration research initiative to their existing Arctic R&D programs. A fundamental underlying driver behind our proposal is the strong belief that observational science alone is not enough to address the impending climate disaster the world is now facing. Active and focused R&D targeted on possible ***mitigation and restoration*** strategies to slow GW are now needed. Our proposal first describes *why* the Arctic, including its sea ice in particular, appears to be a critical leveraging element in the rate of GW going forward. The proposal then describes some initial data suggesting there may be safe and reversible ways in which Arctic sea ice could potentially be preserved and possibly restored. If these data are correct, and considerably more research is needed to verify and potentially extend such preliminary findings, then a coordinated effort by multiple Federal Agencies (see below) can play a critical and coordinated role in enabling the U.S. to be at the forefront of a multi-national effort to slow GW thereby buying time for global decarbonization. We propose that the U.S. take the lead in developing and coordinating an international response to mitigate Arctic sea-ice loss and its accelerant effect upon GW and the climate change crisis. We believe this proposal is consistent with the spirit and intent of the recent National Academies of Science, Engineering and Medicine report, "Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance (2021)", which focusd attention on atmospheric versus surface albedo modifications [1].

Put simply, our proposal is for more ***action-oriented*** basic and applied research to directly address the possibilities of restoring Arctic sea ice to slow global warming. **We strongly recommend that in this time of Arctic crisis the national Biden-Harris Administration climate action plan embrace a more pro-active research and development agenda, an agenda incorporating the goal of potentially restoring Arctic sea ice to its more historic norm.**

The Arctic's natural environment, its indigenous peoples and flora and fauna are in desperate need of help. Arctic ice loss has reached crisis proportions. Studies have shown that the Arctic sea ice albedo (reflectivity) feedback has become a driver of GW, not merely a consequence of it. In the next five-years **we believe we must lean forward to understand both the science and engineering of safe and effective Arctic sea ice restoration techniques**

## 2.0 NEEDS STATEMENT

In summarizing the annual 2020 Arctic Report Card, NOAA stated that "The sustained transformation to a warmer, less frozen and biologically changed Arctic remains clear" [2]. The Arctic has played a central role in keeping the global climate relatively stable throughout human

history. GW is upsetting this stability, causing a dramatic reduction in Arctic sea ice, land ice and snow, thereby impacting the local Arctic ecosystem, infrastructure, and the four million populating the region (including indigenous peoples) while amplifying global warming [3].

This loss of ice and snow is increasing the absorption of solar radiation by land and ocean, causing the Arctic to warm more than twice the global average (Arctic amplification), and releasing GHG from the thawing of land and offshore permafrost (with combined reserves of five times the amount of $CO_2$ equivalent to that in the atmosphere) [2,4,5,6.] With warming of the Arctic, a number of feedback loops have been established that enhance Arctic amplification. A sea ice reflectivity feedback loop from heating of the ocean contributes the equivalent of an additional 25% of global $CO_2$ emissions to the atmosphere (based on anthropogenically derived $CO_2$ emissions from 1979 to 2008) [7]. Similarly, a land ice/snow reflectivity feedback loop from heating of the land is estimated to contribute an additional 25% equivalent of global $CO_2$ emissions to the atmosphere [8].

In addition to a land reflectivity feedback, an accelerating and potentially irreversible permafrost carbon-climate feedback loop may also be underway with the rapid increase of microbial breakdown of ice-age land-based organic matter to methane and $CO_2$ and the release of methane from the permafrost residing on the shallow east Siberian Arctic Ocean shelf (microbial breakdown of organic matter and melting of methane hydrate) [9,10, 11]. A covering of sea ice over the East Siberian Arctic Shelf has historically helped maintain the quantity of methane released but with ice loss the potential of irreversibly releasing large amounts of methane becomes more plausible [6, 12,13]. This phenomenon is still under assessment [8, 12,13]. Arctic warming is also increasing Arctic wildfires (consuming both plants and soil organic matter) releasing large amounts of $CO_2$ and black carbon, further enhancing permafrost thaw [14,15,16]. Also, about 20% of Arctic land permafrost is vulnerable to abrupt permafrost thaw producing thermokarst lakes as ground subsides and fills with water [17, 18, 19]: rapidly decomposing organic matter and releasing methane and $CO_2$ to the atmosphere. Sea ice decline and associated changes in Arctic regional climate are drivers of changes to tundra and boreal forest ecosystems with boreal forests expanding into tundra and differential growth of shrubs in tundra [20, 21]. These changes complicate the projection of tundra vegetation in cycling carbon as permafrost degrades (up-take or release of carbon to the atmosphere by vegetation) [13, 21]. This rapid decomposition of permafrost along is changing the Arctic from a carbon sink to a carbon source and contributes to Arctic amplification and GW [22, 23, 24]: a scenario that may be slowed with effective mitigation techniques [13]. The link between sea-ice loss and rapid thawing of permafrost is evident not only currently but is also noted in the paleoclimate record [25, 26].

Unfortunately, GHG emitted from decomposition of permafrost has not been included or is underestimated in the majority of models used to predict future climates [17, 27, 28]. The importance of thawing permafrost was addressed by climate scientists to policymakers during a U.S. State Department conference in 2015 [29, 30]: also testifying on the severe impact of loss of sea ice to the Arctic, global warming, and national security before the Senate Commerce Science and Technology Committee in 2020 [31]. Resolving the loss of Arctic sea ice is imperative to prevent thawing permafrost from reaching a tipping point.

Arctic amplification also impacts atmospheric and ocean circulation patterns, such as weakening of the jet stream and slowing of the Atlantic Meridional Overturning Circulation (AMOC) that circulates water between the Arctic and Antarctica, causing changes to weather patterns in the

Northern Hemisphere and possibly globally [32, 33]. A weakened polar jet stream has been linked to the extreme weather events of 2018 [33]. Temperatures in the southwest United States rose above 37.8ºC (100ºF) for days, heavy rains and floods inundated the mid-Atlantic states, and California experienced unprecedented droughts and wildfires. The Southwest witnessed a persistent heat wave, and the mid-Atlantic endured heavy flooding. Japan, Scandinavia, and much of Europe had persistent heat waves leading to wildfires in Greece. A slowing of the AMOC would cause cooler weather for Europe and potentially increase the risk of the collapse of the Western Antarctic Ice Sheet increasing sea level rise by 3 meters (9.8 ft) [34, 35, 36]. There is "...the possibility that rapid and unstoppable sea-level rise from Antarctica will be triggered if Paris Agreement targets are exceeded" [37].

Changes in the Arctic are also displacing Arctic peoples and threatening their food security, as well as leading increasing tensions in the area that threaten U.S. national security. Both Russia and Canada have proposed charging for passage through the Northern Sea Route and Northwest Passage, respectively. Russia is revitalizing its northern fleet and bases in anticipation of increased military activity to reinforce Russia's position with the threat of force. China is pursuing economic interests in the Arctic by partnering with Arctic nations and sees itself as a "near-Arctic" country with equal rights to develop the region's resources, engage in scientific and other projects, and participate in regional governance. Additionally, approximately 70 percent of the infrastructure in the global Arctic region is built on permafrost and is susceptible to severe damage from thaw-related ground instability. Damage to buildings, power stations, pipelines, manufacturing facilities, roads, and railways have a value estimated to be in the $100's of billions.

Left unchecked, GW will exceed the 1.5°C (2.7°F) target set by the IPPC for 2100 [38], resulting in food and water shortages, sea-level rise, damage to infrastructures and the environment, mass human migrations, and destabilization of governments, all threatening U.S. national security interests [39,40,41,42,43].

***Implementation of a mitigation strategy is urgently needed within this decade to prevent effects of Arctic amplification like permafrost thaw and shift of boreal forests from reaching a tipping point***.

## 3.0 OUR PROPOSAL: A MULTI-AGENCY COORDINATED R&D INITIATIVE

We propose, and hope the Biden-Harris Administration will support, the establishment of a focused multiagency R&D program to develop technologies to restore Arctic sea ice to near historic pre-industrial norms. Such an effort, if successful, could slow Arctic amplification, providing some stability to the Arctic region and thereby buy time for the international community to develop more fundamental global economic mitigation efforts and move rapidly from a fossil fuel economy to one based on renewable energy sources. Much effort has been focused on reducing and eventually eliminating the use of fossil fuels, an essential effort that must be seriously accelerated. A recent IPCC report finds that global net $CO_2$ emissions would need to go to zero by 2055 to have a chance of keeping warming below 1.5° C (2.7°F). This does not seem economically or politically realistic. While much more needs to be done to mitigate GW in the short term, restoration of Arctic ice would complement and work in concert with reducing fossil fuel use along with other mitigation efforts to reduce atmospheric GHG. ***We need to use every safe and effective tool in the toolbox to win the climate crisis battle.***

## 4.0 PROGRAM DESCRIPTION - A NEW FEDERAL INITIATIVE: NATIONAL ARCTIC ICE RESTORATION INITIATIVE (NAIRI)

We propose the U.S. take a strong international leadership position in addressing Arctic climate issues and the possibility of ice restoration. We propose the U.S. establish a new research and development (R&D) initiative inspired by NOAA's National Hurricane Center (NHC) where both intramural and extramural scientists perform extensive modeling and monitoring research, and engineers develop mechanisms to deal with the destructive forces of hurricanes. This new R&D initiative, NAIRI, would be focused on Arctic climate restoration. ***NAIRI would be a multiagency coordinated effort comprised of NASA, NSF, NOAA, DoE and DoD*** earth sciences and relevant allied programs associated with climate change and climate modeling. Annual funding for NAIRI would be at 2021 levels of appropriated budgets to the above Agencies ***augmented by an aggregated total of $283M over 5 years.*** Augmented funds would be apportioned through NAIRI among participating Agencies and devoted to R&D into methodologies and demonstration projects designed to restore Arctic ice. NAIRI would also place significant emphasis and resources on updating and modernizing climate models incorporating a more accurate representation of the contribution of Arctic climate changes and Arctic ice representation in global warming models, thus improving prediction accuracy and capabilities. NAIRI would solicit and select concepts for research and projects from government, academic, non-profit and industry organizations in keeping with the standard practices currently used by federal agencies.

Given the predicted enormous deleterious impacts of GW and associated climate changes, NAIRI would provide a coordinated and rigorous U.S. national multi-Agency R&D effort to understand the potential risks and benefits associated with proposed climate intervention approaches. It is important that the nation, and the world, have a variety of tools to use to avoid the disastrous impacts of GW on humans and all ecosystems. Only through R&D investments can such understanding be gained. We further propose that NAIRI invest in experimental efforts designed to actively and safely geoengineer climate restoration through a variety of potential approaches. Approaches for restoration would be selected through solicitation. Initial feasibility of such approaches, mentioned here as proof of principle, was recently shown by a technology proposed by the Arctic Ice Project [44,45]. Initial laboratory and field studies along with preliminary modeling indicate that these technologies have the potential to sufficiently restore Arctic sea ice without the climate disruptions and termination effects associated with typical geoengineering approaches, most notably, stratospheric aerosol injection.

**4.1 Primary Program Goal:** Develop technology(s) to restore Arctic sea ice and increase sea ice albedo, thereby reducing energy absorption in the Arctic which significantly contributes to global warming produced by greenhouse gas emissions. Develop candidate technologies to Technology Readiness Level (TRL) 6-7 (Prototype demonstrated in applicable Arctic environment) by end of Year 5 and transfer technologies to a deployment organization for development to TRL 9.

**Secondary Goal:** Demonstrate feasibility of Arctic sea ice restoration in critical target areas overlying the Eastern Siberian Arctic Ocean shelf to effectively slow release of $CO_2$ and methane from thawing permafrost and associated release of methane from melting methyl hydrates from shallow offshore permafrost.

### 4.2 Program Oversight

We suggest a coordinating Program Office be formed, reporting to OSTP, that would manage, integrate, and coordinate NAIRI projects and activities. Multi-Agency cooperation and communication would be essential to ensure seamless and synergistic efforts by all participating Agencies. An annual report from the Program Office Agency Administrator to OSTP, coordinated through all participating Federal Agencies and Departments, would provide data on progress of the initiative.

## 5.0 AREAS OF RESEARCH

Note that budgets and goals described below are notional and reflect *5-year totals* for each element. Specific budgets, goals, milestones, and requirements will, of course, be finalized by the President's Budget and Congressional appropriations.

### 5.1 Augment Current Studies of Arctic Processes

Climate models continue to underestimate the rate of loss of ice and cryospheric radiative forcing in the Arctic as compared with observations, leading to doubts about how well these models can be trusted to predict future impacts. These underestimates are likely due to an incomplete understanding of cryospheric processes exacerbated by a lack of relevant observations. Augmenting current programs aimed at better understanding Arctic processes is needed in three sub-elements listed below.

### 5.2 Augment Cryospheric Science ($25M)

All the organizations which would participate in NAIRI already have programs that study Arctic processes. We recommend that these be augmented because of the important role of the Arctic in global (at least Northern Hemisphere) weather and climate change. The program element would provide augmented funding for modeling, continued exploitation of current observations and further observations. This program element could be modeled after, or augment, the Cryospheric Science Solicitation of the RESEARCH OPPORTUNITIES IN SPACE AND EARTH SCIENCES – 2020 (ROSES-2020), NNH20ZDA001N-CRYO. The budget presented in the table below are scoped based on funding levels similar to the CRYO Announcement of Opportunity. Since changes in sea ice will likely impact ocean biology, air-sea exchanges, and ocean circulation this program element should provide funding for interdisciplinary research other related solicitations, for example Ocean Biology and Biogeochemistry, Physical Oceanography and Ocean Salinity.

**Goal:** Develop a better understanding of how the Arctic interacts with global weather through atmospheric and oceanic circulation patterns (teleconnections), the effects and consequences of Atlantification (intrusion of warmer Atlantic waters into the Arctic Ocean) regionally and globally, and the extent and potential impacts of carbon release due to thawing permafrost and melting of methane hydrate in the ocean.

### 5.3 Augment Field Measurements ($25M)

This program element would fund additional *in situ* and satellite observations needed to better understand cryospheric processes. Field measurements, especially in the harsh Arctic environment are more expensive. Thus, this program element is notionally scoped at $5M per year with participating Agencies determined by the NAIRI Program Office.

**Goal:** To better understand cryospheric processes with additional *in situ* and satellite observations

### 5.4 Field Mission ($50M)

We propose the US lead an international follow-on mission to MOSAIC. The total 5-year cost of this field mission is estimated to be $50M (U.S. portion) .

**Goal:** Obtain quantitative measurements and characterizations of important dynamic Arctic processes.

## 6.0 DEVELOPING ARCTIC ICE RESTORATION TECHNOLOGIES TO TRL 3 BY YEAR 5

### 6.1 Solicitation, Feasibility and Concept Development to TRL 3 ($38M)

This program element may be modeled after NASA's Innovative Advanced Concepts (NIAC). The NIAC Program "nurtures visionary ideas that could transform future NASA missions with the creation of breakthroughs." This new element would be similar to these but focused on Arctic Ice Restoration. It is suggested that all participating agencies solicit proposals that would restore Arctic sea ice and slow global warming in the Arctic regions and globally and conduct feasibility studies on the potential of selected concepts to restore Arctic sea ice. Projects selected should include lab and small-scale deployments and plans for monitoring appropriate metrics during deployment. Climate modeling, required to develop a scheme to determine the smallest, lowest cost, temporal, and spatial application of the technique that yields the highest benefits, should be included. This task should determine if restoration of Arctic sea ice can effectively slow release of $CO_2$ and methane from thawing permafrost and release of methane from melting methyl hydrates from shallow offshore permafrost.

### 6.2 Technology Maturation of Concept from TRL 3 to TRL 6/7 by year 5. ($40M)

This program element may be modeled after NASA's Game Changing Developments (GCD) Program. The Tipping Point solicitations of the GCD program that "seeks to identify and rapidly mature high-impact capabilities and technologies…". This element is focused on maturing technologies to restore Arctic ice: it is critical to give the scientific community, policy makers and the public confidence the concept(s) selected by NAIRI has the potential of meeting the program goal of developing technology(s) that can preserve and restore Arctic sea ice. Specific goals, requirements, and milestones would be determined by Agency program managers with the assistance of the research community which should devise an efficiency metric with which to judge techniques. It is expected that any proposed techniques would achieve at least TRL 6/7 by year 5. It is anticipated that later stages of deployment may involve public-private partnerships and Nation-state level participation.

The goals of this task would be to mature current concept technology(s) from TRL 3 to TRL 6/7 by year 5 and demonstrate that sufficient levels of ice growth can be developed to significantly reduce Summer Arctic Ocean energy absorption.

### 6.3 Test Deployment of 2 concepts ($30M)

This task should down select and fund 2 concepts for testing at meaningful scale under field conditions. Finally, this task should develop a notional plan on how technology can be applied to scale in the field at TRL 9.

## 7.0 ASSESS THE IMPACTS OF PROPOSED ARCTIC MITIGATION CONCEPTS ON WEATHER, CLIMATE AND ECOSYSTEMS IN THE ARCTIC REGION, NORTHERN HEMISPHERE AND GLOBALLY ($25M)

Modeling impact studies will be conducted to determine how the planet will respond to proposed mitigation concepts. This program element is critical to give the scientific community, policy makers and the public confidence that the effects of these techniques are not likely to produce

undesired or unintended consequences, are easily reversible, and have no termination effects. Studies funded by this program element would necessarily interact with other relevant programs elements. This program element could also provide supplemental funding for interdisciplinary research in other related solicitations. For example, Ocean Biology and Biogeochemistry, Physical Oceanography and Ocean Salinity. It could be modeled after Geoengineering Model Intercomparison Project (GeoMIP). Specific, goals, requirements, and milestones would be determined by the program manager with the assistance of the research community.

## 8.0 COST-BENEFIT AND RISK ANALYSES OF ARCTIC ICE RESTORATION TECHNOLOGY ($50M)

It will be critical to demonstrate to national stakeholders, international partners, and the public that the regional and global damage resulting from further warming and Arctic sea ice loss far outweigh any short-term economic benefits from augmented commercial opportunities due to ice loss. For example, increased fossil fuel extraction in the region would both endanger local habitats and the livelihood of indigenous peoples and contribute to accelerating GHG emissions that the world should be aggressively seeking to limit. This program element would fund researchers to perform cost-benefit analyses that would include the effects on indigenous peoples and Arctic flora and fauna.

## 9.0 NOTIONAL BUDGET AUGMENTATION (TOTAL FOR NAIRI)

Annual funding would notionally be at 2021 levels of appropriate elements of participating Agency budgets ***augmented*** by an aggregated total of $283M over 5 years. *(Please note: this budget is updated from the recent publication "Strawa, A. et al. Arctic Ice Loss Threatens National Security: A Path Forward. Orbis. 10 Aug 2020")*

| **NAIRI BUDGET AUGMENTATIONS ($M)** | **Yr 1 Total** | **Yr 2 Total** | **Yr 3 Total** | **Yr 4 Total** | **Yr 5 Total** | **TOTAL Yrs 1-5** |
|---|---|---|---|---|---|---|
| **Area of Research** | | | | | | |
| Augment Current Studies of Arctic Processes | | | | | | |
| Augment Cryospheric Science (all agencies) | **5** | **5** | **5** | **5** | **5** | **25** |
| Augment Field measurements (all agencies) | **5** | **5** | **5** | **5** | **5** | **25** |
| Field mission | **2** | **5** | **13** | **14** | **13** | **50** |
| | | | | | | |
| **Achieving Arctic Ice Restoration Technologies To TRL 6/7 By Year 5** | | | | | | |
| Solicitation, Feasibility and Concept Development to TRL 3 (all agencies) | **3** | **5** | **10** | **15** | **5** | **38** |
| Technology Maturation of Concept to TRL 6/7 (NASA) | **3** | **7** | **10** | **10** | **10** | **40** |
| Test Deployment of 2 Concepts | **0** | **0** | **10** | **10** | **10** | **30** |
| | | | | | | |
| **Assess impacts of Arctic Mitigation Concepts to Planet (all agencies)** | **5** | **5** | **5** | **5** | **5** | **25** |
| | | | | | | |
| **Cost-benefit and Risk Analyses of Arctic Restoration Technology (all agencies)** | **10** | **10** | **10** | **10** | **10** | **50** |
| | | | | | | |
| **Total across all agencies** | **33** | **42** | **68** | **74** | **63** | **283** |

## REFERENCES


[1] National Academies of Sciences, Engineering, and Medicine (2021). Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press.

[2] Arctic Report Card (2020). NOAA. https://arctic.noaa.gov/Report-Card/Report-Card-2020

[3] By 2050, 70% of Arctic infrastructure is located in regions at risk from permafrost thaw and subsidence See: IPCC, (2019). Technical Summary. Pörtner, H.-O, et al. (editors). In press. https://www.ipcc.ch/srocc/chapter/technical-summary/

[4] Hays, B. (2018). Arctic warming at twice the rate of the rest of the planet, UPI Science News, Dec. 12, 2018, https://www.upi.com/Science_News/2018/12/12/NOAA-Arctic-

[5] Schaefer, K. (2020). Methane and Frozen Ground. National Snow and Ice Data Center. 2020. https://nsidc.org/cryosphere/frozenground/methane.html

[6] Wadhams, P. Chapter 9, Arctic Methane, a Catastrophe in the making, Oxford University Press, 2017

[7] Pistone, K. et al. (2014). Observational determination of albedo decrease caused by vanishing Arctic sea-ice. Proc. Nat. Acad. Sci., 111 (9), 3322-6.

[8] Wadhams, P. A Farewell to Ice, Oxford University Press. 2017

[9] Methane is 28-36 times more potent than $CO_2$ as a GHG over 100 years. See: Environmental Protection Agency. Climate Change Indicators: Greenhouse Gases. https://www.epa.gov/climate-indicators/greenhouse-gases

[10] Steinbach, J. et al. (2021). Source apportionment of methane escaping the subsea permafrost system in the outer Eurasian Arctic Shelf. PNAS 2021 Vol. 118 No. 10. https://doi.org/10.1073/pnas.2019672118

[11] Shakhova, N. et al. (2010). Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. *Science* 327, 1246–1250.

[12] Shakhova, N. et al. (2019) Understanding the Permafrost-Hydrate System an Associated Methane Releases in the East Siberian Arctic Shelf, Geosciences, 5 June 2019

[13] Scadel, C. (2020). The irreversible emissions of a permafrost 'tipping point'. Permafrost Carbon. 12 February 2020. Networkhttps://www.carbonbrief.org/guest-post-the-irreversible-emissions-of-a-permafrost-tipping-point

[14] Natali, S. et al. (2021). Permafrost carbon feedbacks threaten global climate goals. Proceedings of the National Academy of Sciences 2021 Vol. 118 No. 21

[15] Liu, Y. et al. (2014). Wildland fire emissions, carbon, and climate: Wildfire–climate interactions. Forest Ecology and Management. Volume 317, 1 April 2014, Pages 80-96

[16] Stone, Maddie. (2020). Arctic fires released more carbon in two months than Scandinavia will all year. Grist. Aug 04, 2020. https://grist.org/climate/arctic-fires-released-more-carbon-in-two-months-than-scandinavia-will-all-year/

[17] Walter Anthony, K. (2018). 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. Nature Communications, 2018, 9:3262

[18] Rodenhizer, H. et.al. (2020). Carbon Thaw Rate Doubles When Accounting for Subsidence in a Permafrost Warming Experiment. Journal of Geophysical Research, Biogeosciences Journal Volume: 125, Issue: 6

[19] Farquharson, L. et al. (2019). Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian High Arctic. *Geophysical Research Letters*, *46*, 6681–6689.

[20] McSweeney, R. February 10. 2020. Tipping Points Explainer: Nine 'tipping points' that could be triggered by climate change. Carbon Brief. https://www.carbonbrief.org/explainer-nine-tipping-points-that-could-be-triggered-by-climate-change

[21] Buchwal, A. et al. (2020). Divergence of Arctic shrub growth associated with sea ice decline. Proceedings of the National Academy of Sciences. www.pnas.org/cgi/doi/10.1073/pnas.2013311117

[22] Schaefer, K. et al. (2011). Amount and timing of permafrost carbon release in response to climate warming, Tellus B: Chemical and Physical Meteorology, 63:2, 168-180 https://onlinelibrary.wiley.com/doi/10.1111/j.1600-0889.2011.00527.x

[23] Reiny, S. (2019). Arctic Shifts to a Carbon Source due to Winter Soil Emissions. Nov. 8, 2019 NASA Earth Science. https://www.nasa.gov/feature/goddard/2019/arctic-shifts-to-a-carbon-source-due-to-winter-soil-emissions

[24] McGuire, A. et al. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. Proceedings of the National Academy of Sciences Apr 2018, 115 (15) 3882-3887

[25] Lawrence, D. et al. (2008). Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. Geophysical Research Letters, Vol. 35, L11506, doi:10.1029/2008GL033985

[26] Vaks, A. et al. (2018). Palaeoclimate evidence of vulnerable permafrost during times of low sea ice Nature, Vol577, 9January2020, pgs 221-225

[27] United Nations Environment Program. "Thawing of permafrost expected to cause significant additional global warming, not yet accounted for in climate predictions." ScienceDaily. ScienceDaily, 27 November 2012. www.sciencedaily.com/releases/2012/11/121127094250.htm

[28] Francis, J. (2018). The Arctic Is Breaking Climate Records, Altering Weather Worldwide. Scientific American, April 2018. https://www.scientificamerican.com/article/the-arctic-is-breaking-climate-records-altering-weather-worldwide/?print=true

[29] Woods Hole Research Center. Scientists warn leaders of dangers of thawing permafrost. Science News, August 27, 2015. https://www.sciencedaily.com/releases/2015/08/150827154413.htm

[30] Holmes, R. et al. (2015). Permafrost and global climate change. Policy Brief. Woods Hole Research Center. June 2015

[31] Francis, J. (2020), Testimony to the Senate Commerce, Science, and Technology Committee Security Subcommittee Hearing on Coast Guard Capabilities for Arctic Security, December 8, 2020. Woodwell Climate Research Center. https://www.woodwellclimate.org/dr-jennifer-francis-testifies-before-the-senate-commerce-science-and-technology-committee/

[32] Sévellec, F. et al. (2017). Arctic sea-ice decline weakens the Atlantic Meridional Overturning Circulation. Nature Climate Change. 31 JULY 2017.

[33] Mann, M. (2019) The Weather Amplifier. Strange waves in the jet stream foretell a future full of heat waves and floods. Sci Am. Mar. 2019

[34] Steffen, W. et al. (2018) Trajectories of the Earth System in the Anthropocene, PNAS, August 14, 2018, vol. 115, no. 33

[35] Lenton, T. et al. (2019) Climate tipping points — too risky to bet against. Nature, Vol 575, pgs. 592-595, 28 November 2019

[36] Hulbe, C. (2020). Between its east and west ice sheets and its peninsula, Antarctica holds enough ice to raise global sea levels by around 60m. Carbon Brief, 14 Feb 2020.

[37] DeConto, R. et al. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. Nature, volume 593, pages 83–89, 05 May 2021.

[38] Yun Gao, Xiang Gao, Xiaohua Zhang. (2017). The 2 °C Global Temperature Target and the Evolution of the Long-Term Goal of Addressing Climate Change—From the United Nations Framework Convention on Climate Change to the Paris Agreement, Engineering, Volume 3, Issue 2, Pages 272-278. https://www.sciencedirect.com/science/article/pii/S2095809917303077

[39] Brown, O. (2008). Migration and Climate Change. International Organization for Migration ISSN 1607-338X. https://publications.iom.int/books/mrs-ndeg31-migration-and-climate-change

[40] Carter, C. et al. (2018), Identifying the Economic Impacts of Climate Change on Agriculture; Annual Review of Resource Economics Vol. 10:361-380. October 2018

[41] Ligtvoet, W. et al., (2017) "Water, climate and conflict: security risks on the increase?" June 2017 https://www.researchgate.net/publication/317687776.

[42] Department of Defense. National Security Implications Of Climate-Related Risks And A Changing Climate. July 2015.

[43] Hjort, J. (2018). Degrading permafrost puts Arctic infrastructure at risk by mid-century. Nature Communications, 2018, 9:5147, DOI: 10.1038/s41467-018-07557-4

[44] Field, L. et al., (2018). Increasing Arctic sea ice albedo using localized reversible geoengineering," Earth's Future, vol. 6, 2018, pp. 882–901, https:// doi.org/10.1029/2018EF000820

[45] Ivanova D. et al. Fram Strait: Possible key to saving Arctic ice. Submitted.

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