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Fram Strait: Possible key to saving Arctic ice

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Abstract

We present a modeling study of the sensitivity of present-day Arctic climate dynamics to increases in sea ice albedo in the Fram Strait. Our analysis reveals a new mechanism whereby enhancing the albedo in the Fram Strait triggers a transition of the regional atmospheric dynamics to a negative Arctic Dipole Anomaly phase. This causes an Arctic-wide ice circulation regime, weakening Transpolar Drift and reducing Fram Strait ice export, leading to thickening of the multi-year ice pack. These findings advance our understanding of the key role that the Fram Strait plays in Arctic climate and highlights a potential path to restoring Arctic sea ice.

Introduction

The Arctic is warming at twice the rate of the rest of the planet, accelerating sea ice loss (1). Sea ice thinning over marginal sea ice areas has caused near-surface warming of 1°C per decade in winter, a positive feedback that increased the Arctic amplification factor by 37% (2). Recent studies suggest that the Arctic sea ice loss weakens and destabilizes the Arctic polar jet stream, impacting the weather in the mid latitudes (e.g changes in storm tracks) (3, 4). Changes in the Arctic may also be transmitted to the lower latitudes through planetary waves, strengthening the tropical jets and displacing the Pacific intertropical convergence zone, causing tropical warming (3, 5). Transition of the Arctic into a seasonally ice-free ocean will potentially not only increase air temperatures and cause precipitation phase changes (6) in the Arctic, but will also affect summer precipitation in Europe, the Mediterranean, and East Asia (7, 8), and increase droughts and wildfire risks in California (9). A recent study estimates that an additional global warming of 0.71 W/m² will be caused by the complete loss of the Arctic sea ice cover, which will accelerate global warming by 25 years (10).

Analysis of sea ice drifts derived from satellite observations shows that the winter increase of sea ice export is correlated positively with the winter Arctic Oscillation (AO) index and negatively with the following September sea ice extent (11). Such correlations are weakened when the sea ice cover is thick enough to resist the anomalous wind forcing caused by different phases of the AO. In order to maintain a fully ice-covered Arctic in the winter, there needs to be an increase in

first-year ice in winter that is thick enough to survive the following summer melt season, compensating for the net deficit in the sea ice area budget (11).

Understanding the dynamics of the atmosphere and ocean over the mid and high latitudes requires a proper model representation of Fram Strait (FS) sea ice transport. In particular, it contributes to rapid changes in the Atlantic Meridional Overturning circulation impacting the mid-latitude weather (12). Fram Strait ice export is dominated by the wind-driven Transpolar Drift (TD) (a major feature of the large-scale Arctic sea ice circulation), which moves thinner sea ice from the east Siberian shelf across the pole towards the Fram Strait. The southward flow of sea ice through the Fram Strait is controlled by the across-strait sea level pressure gradient (2,13,14), which is part of the Arctic Dipole Anomaly (ADA) (15), the second dominant mode of atmospheric variability in the Arctic (16,17) featuring an east-west dipole with a low pressure anomaly centered in the Barents Sea (BS) and Kara Sea (KS) and a high pressure anomaly in the Canadian archipelago (See also Supplementary Text). Intensifying/diminishing the negative anomaly in the BS enhances/weakens northerly winds through the Fram Strait, consequently increasing/reducing the exported sea ice (16).

The strongest sea ice albedo feedback is in the Barents Sea and Kara Sea during the summer season (18). Reduced sea ice albedo in these marginal sea ice areas strengthens Arctic amplification, causing further warming. Our findings show that this may be influenced strongly by the atmosphere-ice-ocean interaction and dynamics over the Fram Strait. We show in Figure 1 that a sea ice albedo perturbation over the FS area (see inset) increases the sea ice albedo significantly over the areas of strongest sea ice-albedo feedback.

Our objective here is to study the impact of increasing the sea ice albedo in order to change the Arctic surface radiation balance so as to reduce the heating of the Earth's surface. Since the Fram Strait plays a key role in the Arctic sea ice mass balance, here we investigate whether the impact of increasing sea ice albedo (19) over the FS can be a key lever in restoring Arctic sea ice and slowing down its export from the Arctic.

Results

Our modeling study uses the National Center for Atmospheric Research (NCAR) fully-coupled Community Earth System Model (CESM) with interactive atmospheric, sea ice, ocean and land components. The broadband sea ice albedo is perturbed by modifying the physical properties of the snow layer in the sea ice model component (see detailed discussion in the Methods section). To establish a present-day baseline for the albedo perturbation experiments we employ a scenario with climatological 2000's greenhouse gases (GHG) and aerosol forcing. We design three types of model experiments: CONTROL case with no changes applied, FRAM case with albedo perturbation in the Fram Strait region, an area of approximately 1% of the Arctic (Fig.1, region enclosed by black lines, see also Fig.S1), and GLOBAL case with an Arctic-wide albedo perturbation. For each experiment we run three-member ensembles initialized from different AO phases and integrated from 2000 to 2080 (See further details in the Methods section). The current study is focused on the FRAM case and we present the analysis of the underlying climate dynamics in the following sections.

Albedo Perturbation

In the FRAM case, an albedo perturbation was applied over an area of 151,200 km² in the Fram Strait region (see inset in Fig.1). The surface albedo perturbation results in an annual albedo increase of about 6-10% over the FS region. There are also significant albedo increases of 2-6%

outside of the treatment region, in areas to the east of Svalbard, and parts of the Barents and Kara Seas (Fig.1a). One possible explanation for these albedo changes beyond the treatment area might be that sea ice with modified physical properties (e.g. modified snow layer and thickened ice) drifts from the FS region toward Svalbard and the BS. Additionally, the resulting albedo in the remote areas may be influenced by the regional changes in thermodynamics and atmospheric dynamics caused by the albedo modification in the FS region. The strongest impact of the albedo perturbation is during the summer daylight season with maximum insolation. Due to enhanced reflectivity of the surface, in summer (JAS, Fig.1b), the albedo increases by ~20%, ~15% and ~5% respectively in the FS, north-west BS and KS. These increases are statistically significant at greater than 90% confidence as tested through a t-test. During the dark winter (JFM, Fig.1c) this effect is lessened. The negative albedo anomaly seen south of FS in the Nordic Seas is most likely due to reduced ice cover as a result of decreased ice export through FS (see Section: Changes in Sea Ice).

Radiation Balance Changes

The objective of perturbing the surface albedo is to change the balance of the surface radiation fluxes in order to reduce the heating of the Earth's surface. Such albedo perturbations have direct impact primarily during the daylight time of the year (March-Sept. in the northern hemisphere polar areas). Once the albedo modification is applied, the response of the surface radiation fluxes is immediate.

The annual cycle of the Arctic ocean heat balance at the surface is dominated by heat loss with annual mean of $\sim -10 \text{ W/m}^2$ (Fig.S2, ANN). During summer, the incoming solar radiation warms the surface and the ocean is gaining heat from about $10\text{-}30 \text{ W/m}^2$ in the central basin to $40\text{-}70$

W/m² in the marginal zones (40-50 W/m² in Fram Strait) (Fig.S2, JAS). The summer (JAS) map of the differences in the net (residual) surface radiation flux between FRAM and CONTROL cases show a reduction over the FS region, ranging from roughly -10 W/m² at Greenland's north-east corner to about -2 W/m² east of Svalbard (Fig.2a). This reduction indicates lower absorption of solar radiation by the surface in the FRAM case.

At the top of the atmosphere (top of the model - TOM) the net (residual) radiation flux in the Arctic is outgoing, or releasing heat in open space and cooling, throughout the entire year (Fig. S3). The heat loss in the CONTROL case in the winter (JFM) is more than -150W/m² basin wide, reducing in the summer (JAS) from -100W/m² in the central basin to -80W/m² at 70°N (including Fram Strait). The radiation changes seen at the surface in the FRAM case, propagate to the top of the atmosphere and manifest as significant increase in the summer residual TOM radiation flux (Fig.2b) over the Fram Strait, Barents and Kara Seas, and Bering Strait regions, outgoing to space ranging from ~10 W/m² over the Fram Strait to 2-8 W/m² over the north Barents Sea. These Arctic radiation balance changes result in cooling surface temperatures (~-1°C) over the Fram Strait, (~-0.4°C) over the Kara Sea, Bering Sea and parts of the Beaufort Gyre regions (Fig.2c). The remote changes in the Bering Strait suggest a teleconnection with the Fram Strait perturbation; investigation of this teleconnection is beyond the scope of the current study.

The changes in the Arctic annual radiation budget components integrated north of 70°N allow us to understand the sources of the radiation balance anomalies in the FRAM case (Fig. 2de, see also Fig.S4, S5 and Table S1, S2). The overall total Arctic annual net surface radiation flux outgoing from the surface in the CONTROL case is -166.6 TW (netSRF, Fig. S4, Table S1). In the FRAM

case it has increased by 2.2 TW or about 1.33% compared to the CONTROL (Table S1). This increase is due to the larger amount of about 4 TW reflected shortwave radiation (SWU, Fig.2d). The rest of the outgoing components from the annual surface budget, the longwave up, latent and sensible heat fluxes, are decreased (LWU, LH, SH, Fig.2d, Table S1). This is most likely a consequence from the reduced solar radiation absorbed by the surface during the summer season due to the increased albedo (Fig.2a). The increase of the outgoing radiation from the surface due to the larger amount of reflected solar radiation implies cooling of the surface and concurs with the cooling anomalies seen in Fig. 2c.

At the top of the model (TOM), the total Arctic annual net radiation outgoing to open space in the CONTROL case is -1,823 TW (netTOM, Fig. S3; CONTROL, Table S2). This amount has increased in the FRAM case by -3.6 TW (0.2%) (netTOM, Fig.2e; FRAM-CONTROL, Table S2) due to the decreased net shortwave radiation (netSW, Fig.2e; Table S2). There is a slight decrease in the net longwave radiation (netLW, Fig.2e, Table S2) at TOM, outgoing to open space, of 0.3 TW (0.01%), most likely due to the less absorbed solar radiation. The increased outgoing radiation at the top of the model indicates cooling of the Earth.

Changes in the Atmospheric Dynamics

The dominant Arctic atmospheric patterns (18) in the winter consist of a high-pressure ridge stretching over the Beaufort Sea and East Siberian Shelf, and strong easterly winds flowing from Eurasia towards the Canadian Archipelago, turning southward around Greenland (Fig.S6, JFM). These atmospheric dynamics transition in the late summer (JAS) to a basin-wide cyclonic system with low surface pressure center near the Canadian Archipelago and counter-clockwise divergent winds (Fig.S6, JAS).

The comparison of the atmospheric dynamics changes in the large-scale and the regional albedo perturbations shows distinct differences which affect the Fram strait ice export in the opposite way (Fig.3). That is, while in the FRAM case the anomalous winds favor reduced sea ice export through the Fram Strait, in the GLOBAL case the atmospheric dynamics increases the export. During summer, when the albedo perturbation has its strongest impact, in the FRAM case there is a dipole pattern of pressure anomalies with a strong positive anomaly centered in the northern Barents Sea, and two negative anomalies centered in the Canadian Archipelago and the Nordic Sea. These pressure anomalies are accompanied by intensified winds from the Barents Sea toward the central Arctic and Beaufort Sea (Fig.3a). This pattern resembles the negative phase of the second dominant mode of variability in the Arctic - ADA, found to be the main driver of the Fram Strait ice export (15,16). It expands and intensifies in the winter into a high-pressure ridge over the Eastern Arctic with intensified winds directed from the Barents and Kara Seas toward the Bering Strait. While in the positive phase of ADA there are intensified anomalous northerly winds across Fram Strait (16), in the negative phase there are intensified anomalous easterly-south-easterly winds, reducing the southward sea ice drift through the Fram Strait (Fig.3ab). In contrast, in the GLOBAL case during winter there is a dipole of low sea level pressure anomaly in the Laptev sea and a high-pressure anomaly in the Canadian Archipelago. In summer, there is a basin-wide positive pressure anomaly centered in the Laptev Sea for the GLOBAL case. In both seasons, the anomalous winds driven by these pressure systems are favoring increased ice export through the Fram Strait (Fig.3cd).

Changes in Sea Ice

The seasonal distributions of the Arctic sea ice concentration and drift (Fig.S7) and sea ice thickness (Fig.S8) simulated in the CONTROL and FRAM cases are in agreement with the patterns known from observations in the 2000's (20, 21, 22). The winter ice pack is with 100% ice concentration basin wide, driven by a clockwise circulation of the Beaufort Gyre and the Transpolar drift moving ice from the Siberian shelf towards the Canadian Archipelago and from the Laptev and Kara Seas towards the Fram Strait (Fig.S7, JFM). In the summer, the ice pack is less compact with maximum ice concentrations of 90% in the Central Arctic, decreasing to 30-40% in the marginal seas. The sea ice drift is reversed compared to the winter, with an anti-clockwise divergent circulation centered over the North Pole (Fig.S7, JAS). The simulated thickness distribution in CONTROL (Fig.S8) represents reasonably the ice thickness distribution observed in the 2000's (22, Fig.1) with thickness of 1.5-2 m at the North Pole, 1-1.5m in the Eastern Arctic, 0.5-1m in the Beaufort Sea. The thickest ice of about 4m is found along the northern coast of Greenland. The ice is thinning by 0.5 m in the melt season.

The enhanced albedo in the Fram Strait (FRAM case) causes a distinct increase in the summer sea ice concentration (12-14%) and sea ice thickness (10-15cm) in the Fram Strait region of the albedo perturbation (Fig4ab, JAS). Significant increases are also found in the areas north and east of Svalbard, and in the Kara and Beaufort Seas. Significant thickening is found in the central Arctic (~4cm) and north of the Canadian Archipelago (~15cm), areas where the multi-year ice pack is usually originating and residing (Fig.4b, JAS). *These thicker ice anomalies persist in the winter (Fig.4b, JFM) suggesting that the summer build up has survived the melt season to become multi-year ice.* These non-local ice pack changes are related to the changes in the sea ice circulation (Fig4a). An intensified drift moves the ice from the North Atlantic sector towards the central Arctic

during the summer. In the winter the Transpolar drift and the Beaufort Gyre have weakened, contributing to reduced sea ice export through the Fram Strait, therefore reducing ice concentration and thickness in the Nordic Seas.

The impact of the sea ice albedo perturbation on the climatological mean Arctic Total Sea Ice Area (TSIA) is modest - about 2398 km² (0.27%) increase. This is expected since the sea ice albedo increase mainly affects the existing sea ice growth, and is unlikely to create conditions in the open ocean for new ice to freeze and expand. However, the climatological mean Arctic Total Sea Ice Volume (TSIV) has increased by 76 km³ (0.52%), or at twice the rate of the increase in TSIA, revealing that *the major impact of the sea ice albedo enhancement is thickening of the sea ice pack*, potentially increasing its multi-year fraction and longevity. The simulated seasonal cycle of the Arctic TSIA in the CONTROL reference case shows close agreement to the observed 2000-2015 monthly climatology of the NASATEAM SSM/I satellite estimate (Fig.4c). The simulated TSIV is in close agreement with the PIOMAS reanalysis during the summer but it underestimates the winter quantities (Fig.4d).

The simulated mean annual ice export in the CONTROL case is 627,581km² which underestimates the observed long-term annual mean (23) of 883,000km² (Fig.4e). Local thickening of the sea ice in the Fram Strait as well the changes in the Arctic ice circulation lead to a reduction of the annual mean ice export by 14,979km² (2.4%) in the FRAM case while in contrast, the case of basinwide thickening of the Arctic ice pack (GLOBAL), the sea ice export has increased by 235,491 km² (37.5%).

Discussion

Enhancing sea ice albedo ($\sim 20\%$) in the Fram Strait (FS) reflects more of the incident solar radiation, which locally reduces ($\sim 10\text{W/m}^2$) the solar radiation absorbed by the surface in the summer, and increases ($\sim 10\text{W/m}^2$) the outgoing radiation at the top of the model (TOM), resulting in cooling of the surface ($\sim -1^\circ\text{C}$) and of the atmospheric column. These radiation balance changes extend beyond the Fram Strait region of albedo perturbation, to the Barents Sea and Kara Sea both of which are areas that are highly sensitive to albedo feedback amplification (18). The impacts of regional albedo modification in Fram strait comprise of more compact (12-14%) and thicker (15cm) ice pack not only locally in the area of albedo perturbation in the Fram Strait, but also beyond, into the north-western part of Barents Sea, central Kara Sea, Beaufort Gyre and north of the Canadian Archipelago.

The mechanisms underlying the remote impacts seen in the Arctic ice cover (Fig. S9) may be explained by the thermodynamics-atmospheric dynamics interaction (15). The radiation balance anomalies in the Barents and Kara Seas cause a cooling surface temperature anomaly (-0.4°C) which in turn creates a high surface pressure anomaly centered in Kara Sea, triggering a negative phase of the Arctic Dipole Anomaly. This drives south-westerly winds from the Barents and Kara Seas, along the Fram Strait towards the Beaufort Sea. The high-pressure anomaly extends and intensifies in winter into a high-pressure ridge over the eastern Arctic with intensified winds directed towards the Bering Strait. This atmospheric dynamic modifies the wind-driven large-scale sea ice circulation, weakening the Transpolar Drift and the pressure gradient across the Fram Strait and consequently decreasing the export of sea ice through the Fram Strait by $14,979\text{km}^2$ (2.4%).

Although the albedo perturbation directly impacts sea ice cover during the summer season (daylight period) its indirect impacts persist in the winter (e.g. positive ice thickness winter anomalies are observed in the Beaufort Gyre) which suggests that strengthening the sea ice during the melting season will favor growth of the multi-year ice pack in the Arctic. These regional changes do not significantly disturb the natural seasonal cycle of the Arctic-wide total sea ice area and volume. Comparing the regional albedo modification of the FRAM case to an large-scale Arctic-wide albedo perturbation scenario in the GLOBAL case (19) reveals that the changes in the atmospheric dynamics are different in the two cases. While in the FRAM case the atmospheric dynamics causes the sea ice to drift towards the central core of the Arctic basin and reduces the Fram Strait ice export, thus keeping the sea ice within the Arctic basin, in the GLOBAL case the dynamics drives strong Transpolar Drift and increased Fram Strait ice export. This creates a risk of excessive ice melt in the Nordic Seas, freshening the ocean stratification with implications for the Atlantic meridional overturning circulation (12).

Our findings suggest that the *Fram Strait albedo enhancement has the capability to reduce the positive albedo feedback contribution to the Arctic amplification in the areas that are most sensitive to albedo feedback such as the Barents, Kara and Beaufort Seas, and holds a potential for Arctic sea ice recovery.* The shallow areas of Barents and Kara Seas with large deposits of frozen methane clathrates in the ocean bed are prone to outgassing in a warming scenario (24). Our results show that the albedo perturbation over Fram Strait helps to increase summer ice cover over these areas.

280 There are several limitations of this study. Longer integrations are necessary to spin up the deeper
281 ocean layers to better represent the Earth system variability at longer time scales (>80years). The
282 significance of the results would greatly improve if a larger number of ensemble members (>3)
283 are used to better resolve the signal of the regional albedo perturbation in the Fram Strait, which
284 is small compared to the natural internal variability. More realistic present-day and future climate
285 scenarios with greenhouse gas forcing, transient variability is needed for a more accurate
286 modeling, simulation and impact assessment.

287
288 Our results will help to develop the detailed albedo parameterization in sea ice models that will
289 simulate the properties and behavior of albedo enhancement material applications. Ongoing
290 studies analyzing the impacts of sea ice albedo perturbation over the Fram Strait on the global
291 climate, over tropical and temperate regions, and on the intrinsic modes of climate variability, are
292 underway and will be reported separately.

Methods

Experimental Design

We use the National Center for Atmospheric Research Community Earth System Model (CESM) version 1.2 including Community Atmosphere Model version 4 (CAM4), Community Ice Code version 4 (CICE4), Parallel Ocean Program version 2 (POP2) and Community Land Model version 4 (CLM4) components. The model grid resolution is ~1deg in all model components. To establish a present-day baseline for the albedo perturbation experiments we employ a scenario with climatological 2000's greenhouse gases (GHG) and aerosol forcing. The sea ice albedo perturbation was modeled using the “delta Eddington” shortwave parameterization in the sea ice model component CICE of CESM (25). This involved assigning different physical properties to the snow layer in the albedo perturbation area. Particularly, two input model parameters were used: **R_{snw}** - base snow grain radius, a tuning parameter which is related to broadband snow albedo and **rsnw_mlt_in** – the maximum melting snow grain size (26). The experimental design includes three types of experiments: a control run (CONTROL) where no albedo perturbation is applied, an albedo perturbation experiment localized in the Fram Strait (FRAM) and an Arctic-wide albedo perturbation experiment (GLOBAL). The Fram strait region where the albedo perturbation is applied (78.05°N-80.87°N and 18.75°W-12.5°E) has an area of 151,200km² (See Fig.1 region in black lines and also Fig.S1, outlined with magenta lines). In the CONTROL case we use the default model settings for **R_{snw}** and **rsnw_mlt_in** of 1.5 and 1500, respectively. In the albedo perturbation cases we set those parameters to 2.5 and 200, respectively, over the area of the albedo perturbation. Both of these parameter changes act to reduce the grain size of the snow, modifying the optical properties of the snow layer in a way to increase the snow/ice albedo. This results in a different albedo than the untreated sea ice cover. In the perturbation experiment the underlying assumption is that wherever there is sea ice in the treated region, the sea ice albedo perturbation

would apply. During the melt season, with sea ice retreating and uncovering ocean waters, the sea ice albedo perturbation diminishes.

The climate system has strong internal natural variability, which may be large over short time scales. In the Arctic, the dominant mode of variability is the AO, defined as the first empirical orthogonal functions mode of the winter surface pressure pattern in the Northern hemisphere. It is characterized by Polar low- and high-pressure centers in the mid-latitudes (27). The effects of the FRAM perturbation to sea ice albedo were expected to be much smaller than the effects of the AO. Therefore, in order to detect the FRAM effects within the possible ranges of climate variability, an ensemble of three members initialized at each of the phases of the AO (i.e., the positive, negative, and neutral phases) was carried out. Ideally, this initialization approach sets the ensemble members' AO variability out of phase with each other and when creating their ensemble mean, they would cancel and thus eliminate or reduce the signal of the dominant AO pattern. The initial states were chosen from the last decade of an 80-year spinup control simulation. The simulations are fully coupled present day climate simulations such that they evolve continuously and on their own trajectory initialized in the year 2000 and integrated forward for 80 years. The constant part in the simulations is the GHG forcing (using GHG climatology for the 2000s) which implies that we are running a scenario in which we constrain the GHG forcing to be the same as 2000 GHG forcing. Our primary focus in this study is the analysis of the FRAM sensitivity experiment, but when applicable we also use results from the GLOBAL experiment to provide additional insights. The analysis of the results is presented in terms of ensemble mean characteristics. Each of the major experiment's (CONTROL, GLOBAL and FRAM) ensemble mean time series were created by averaging the three-member ensembles initialized from neutral, negative and positive AO phases. The ensemble spread was defined as minimum and maximum values of the ensemble

members. Annual and seasonal climatologies were calculated for the period 2001-2080, excluding the first year of integration (year 2000) to reduce the impact of the initial adjustment. The model Arctic total sea ice area is defined as the cumulative sum of the northern hemisphere grid cells areas multiplied by the ice fraction where it exists. The Arctic total sea ice volume is the cumulative sum of the grid cell volumes, calculated as the sea ice area multiplied by the mean grid cell sea ice thickness. To compare the simulated quantities to the observed Arctic sea ice state, we used National Snow and Ice Data Center (NSIDC) SSM/I satellite data set for sea ice concentration (2000-2015) retrieved with the NASATEAM algorithm (28) and Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) reanalysis of the sea ice volume (2000-2019) (29,30).

Radiation Balance Computations

The net surface flux is derived as the sum of the net shortwave radiation (downwelling + upwelling shortwave radiation) and the net longwave radiation (upwelling + downwelling longwave radiation), latent and sensible turbulent heat (upwelling). The top of the model (TOM) net radiation is calculated as the residual of the net shortwave radiation - net longwave radiation. The positive/negative direction is down/up.

Statistical Analysis

The significance of the differences between the ensemble mean seasonal and annual climatologies of the experiments is evaluated via two-tail t-test with 90% confidence level.

Data Availability

Data used in the current study are available at:

<http://climformatics.com/FramPaper2021/EnsembleMeans.tar.gz>

<http://climformatics.com/FramPaper2021/TimeSeries.tar.gz>

Code Availability: The codes for the figures will be made available upon request.

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Data availability: The model data used in the current study are available in NetCDF format at:

<http://climformatics.com/FramPaper2021/EnsembleMeans.tar.gz>

<http://climformatics.com/FramPaper2021/TimeSeries.tar.gz>

Figures and Tables

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474 **Fig. 1.** Seasonal maps of the surface albedo perturbations (FRAM-CONTROL differences) in %:
 475 a) annual, b) summer (July-August-September), and c) winter (January-February-March). Only
 476 the statistically significant differences at 90% confidence level are shown in color. The Fram Strait
 477 treatment region is outlined with black lines.

478

Fig. 2. Arctic radiation balance changes (differences between FRAM and CONTROL ensemble means) due the sea ice surface albedo perturbation: Summer (JAS) mean climatology differences maps of – a) residual (net) surface radiation flux; b) residual TOM radiation flux; c) surface temperature (TS). Only significant values with 90% confidence level are colored. Changes in the Arctic annual radiation balance components integrated north of 70°N: d) surface radiation balance anomalies; e) TOM radiation balance anomalies. LWD - longwave down; LWU -

489 *longwave up; LWnet - net longwave radiation; SWD - shortwave down, SWU - shortwave up;*
490 *SWnet - net shortwave radiation; LH - latent heat; SH - sensible heat; netSRF - residual surface*
491 *energy; netTOM - residual energy at top of the model. The FRAM-CONTROL differences are*
492 *taken from the absolute values of the components. Positive/negative anomalies indicate*
493 *increase/decrease in the energy components.*

494

Fig. 3. Changes in the seasonal sea level pressure and surface winds: a) JAS FRAM-CONTROL; b) JFM FRAM-CONTROL; c) JAS GLOBAL-CONTROL; d) JFM GLOBAL-CONTROL.

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a)

c)

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b)

d)

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504 **Fig. 4.** Arctic sea ice changes: Maps of the changes in seasonal sea ice: a) concentration and ice
 505 drift velocities; and b) thickness. The significance of the differences is evaluated with *t*-test with
 506 90% confidence level. Annual cycles of the: c) Arctic total sea ice area, d) Arctic total sea ice

507 volume. e) Annual time series of Fram Strait sea ice area export in CONTROL, GLOBAL and
508 FRAM. Solid lines are the ensemble mean annual time series, dashed are the climatological means,
509 the shadings represent the ensemble spreads.

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513 **Supplementary Materials**

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515 See attached file

Figures

Figure 1

Seasonal maps of the surface albedo perturbations (FRAM-CONTROL differences) in %: a) annual, b) summer (July-August-September), and c) winter (January-February-March). Only the statistically significant differences at 90% confidence level are shown in color. The Fram Strait treatment region is outlined with black lines.

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Arctic radiation balance changes (differences between FRAM and CONTROL ensemble means) due the sea ice surface albedo perturbation: Summer (JAS) mean climatology differences maps of – a) residual (net) surface radiation flux; b) residual TOM radiation flux; c) surface temperature (TS). Only significant values with 90% confidence level are colored. Changes in the Arctic annual radiation balance components integrated north of 70°N: d) surface radiation balance anomalies; e) TOM radiation balance anomalies.

LWD - longwave down; LWU - longwave up; LWnet - net longwave radiation; SWD - shortwave down, SWU - shortwave up; SWnet - net shortwave radiation; LH - latent heat; SH - sensible heat; netSRF - residual surface energy; netTOM - residual energy at top of the model. The FRAM-CONTROL differences are taken from the absolute values of the components. Positive/negative anomalies indicate increase/decrease in the energy components.

Figure 3

Changes in the seasonal sea level pressure and surface winds: a) JAS FRAM-CONTROL; b) JFM FRAM-CONTROL; c) JAS GLOBAL-CONTROL; d) JFM GLOBAL-CONTROL.

Figure 4

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